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Considerations of Health Benefit-Cost Analysis for Activities Involving Ionizing Radiation Exposure and Alternatives

A Report of

Advisory Committee
on the
Biological Effects of Ionizing Radiations

Assembly of Life Sciences
National Research Council
National Academy of Sciences

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs
Criteria and Standards Division

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The report deals with development of methodolgy for the health benefit-cost analysis of activities that result in radiation exposure to humans. It attempts to frame the problems and to communicate the necessary elements of the complex technical process required for this method of analysis. The main thrust of the report is to develop a methodology for analyzing the benefits and costs of these activities. Application of the methodology is demonstrated for nuclear power production and medical uses of radiation, but no definitive analysis is attempted. The report concludes that benefit-cost analysis can be effectively applied to these applications and that it provides a basis for more informed governmental decision-making and for public participation in evaluating the issues of radiation exposure. It notes, however, that for cases where national policy is involved, decisions must inevitably be made on the basis of value judgements to which such analyses can make only limited contributions. An important conclusion is that a significant reduction in radiation exposure to the population is apparently achievable by development of methods for eliminating unproductive medical X-ray exposure.

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NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose [illegible] are drawn from the Councils of the National Academy of Sciences, the [illegible] Academy of Engineering, and the Institute of Medicine. The members [illegible] [illegible] responsible for the report were chosen for their special [illegible] [illegible] with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

This report of the health benefit-cost analysis of exposure to low levels of ionizing radiation and the application of various methods of such analysis was done under the auspices of the National Academy of Sciences (NAS) at the request of the Environmental Protection Agency (EPA). The report defines the over-all problems of such an analysis of benefit-cost, describes the need for such analysis and applies methods described to illustrative examples.

The Committee has endeavored to ensure that no sources of pertinent knowledge or expertise were overlooked in its study. During the course of its deliberations, the Committee solicited the opinions and counsel of several individual scientists and others with information needed for a complete overview of the problem.

The subcommittees or individuals chiefly responsible for the preparation of the more specialized chapters in this report are as follows:

Chapter III.	Subcommittee on Concepts Joseph E. Rall (Chairman), Michael S. Baram, J. Martin Brown, George W. Casarett, Murray Eden, Anthony C. Fisher, John V. Krutilla, Edward B. Lewis, and R. Talbot Page.
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SUMMARY AND RECOMMENDATIONS

SUMMARY

It must be recognized that in discussing the possible usefulness of benefit/cost analysis for radiation regulation, we are dealing with data ranging from the known to the nebulous, of issues ranging from the practical to the purely ethical, and of problems ranging from local to global and from the recent past to the indefinite future.

For some questions, benefit/cost analysis can provide unequivocal answers. For instance, if it were determined, statistically or theoretically, that mass mammography screening programs induce more cancers than they detect, then such programs should be halted. On the other hand, if studies show that they detect twice as many cancers as they induce, but that the dollar cost of the program, applied elsewhere, would result in a greater number of cancer detections, the problem becomes more complicated but still solvable. Again, if a non-radiation technique, such as ultrasonography or thermography, were shown to be as effective as x-rays in detecting cancer and to have no deleterious side effects, this would clearly be the preferred technique.

In the middle ground are problems for which benefit/cost analysis may provide information essential to informed decision-making, but can provide no final answers. A hypothetical example might be that of airport x-ray inspection devices. Analysis can yield data on the possible harm, to passengers and attendants, of such devices, on the dollar costs of the program, and on the frequency and costs of airplane hijacking before and after the program was instituted; but the value judgment must be a political-ethical decision.

Perhaps the most important problems are those for which there are no data--the effect of today's radiation ten generations hence, the probability of a nuclear meltdown, the future buildup of nuclear wastes--but, at best, only guesses which may be off by several orders of magnitude. Here, benefit-cost analysis cannot be done in terms of dollars or other common units but, with a different focus, it can identify issues which must be recognized if rational decisions are to be made. The questions of who pays (rural people, future generations) vs. who benefits (city people, present generation); of maximum and minimum possible harm from a given course of action; of alternative courses of action, can be spelled out.

This suggests a three-fold responsibility of federal regulatory agencies: 1) to promulgate regulations based on benefit/cost analysis, when such analysis can provide clear answers; 2) to provide legislators with all relevant benefit/cost data in areas where such data alone do not resolve the question; and 3) to bring to public attention the social and ethical benefit/cost considerations, for which quantification is impossible.

Benefit/cost analysis need not be undertaken if: 1) of two equally beneficial alternatives, one is clearly less costly in both health effects and money; 2) there is, in fact, no measurable alternative; or 3) society has determined either that a given risk, e.g., nuclear meltdown, is unacceptable, however slight the odds or great the benefit, or, conversely, that the benefits of nuclear power outweigh the costs, however great.

Clearly, a basic question arises in any attempt to apply benefit/cost analysis to problems where data are largely conjectural or where ethical considerations are paramount: will such an analysis help by contributing some light to hitherto obscure areas, or will it hurt by focusing attention on quantifiable parameters at the expense of less easily definable but more important areas? For instance, is the attempt, which many have made, to assign a monetary value to a human life helpful in at least providing an economic baseline for analysis, or harmful in making an insoluble problem seem manageable?

It seems unlikely that a benefit/cost analysis based on translation of death and disability into lost work-years, or aesthetics into real estate prices, which resulted in a ratio of one or greater would be generally convincing given the necessarily arbitrary and narrow nature of the assigned values. However, if by even such analysis the benefit/cost ratio comes to less than one, it would suggest that, in fact, the aggregate of quantifiable and unquantifiable costs must, to a greater degree than indicated by the ratio, outweigh the benefits.

Nonetheless, there are cogent reasons for society to attempt health benefit/cost analysis for major technological applications involving radiation exposure of the population in comparison with feasible alternatives which involve less or no radiation exposure. Such analyses could facilitate rational and cost-effective safety and control procedures and the avoidance of health hazards and economic dislocations associated with excessive or inadequate expenditures in relation to risk. Health benefit/cost assessments, even though present data are incomplete, can provide some guidance to decision-makers, direct attention to gaps in knowledge, indicate priorities for research and stimulate the accumulation of needed data and analysis, and contribute to public understanding of the relevant issues and problems.

Although there are great benefits to be derived from the use of various radiation technologies, there are also costs. In one form, these costs arise as a risk of adverse health effects to members of the population. This risk can be stated as a probability which, when applied to the population at risk, gives the number of adversely affected persons. This adverse effect is a social cost and, in principle, can be expressed as the monetary cost of the adverse health effect. Additional private resource costs incurred in the provision of these benefits from the various radiation technologies are, of course, also included in the total social costs. These are the terms defining health benefits and health costs in this report.

This report deals with health benefit/cost analysis in terms of the needs, problems and methodological approaches of the times, the concepts and parameters, ethical considerations, and regulations governing the deleterious agents involved. It illustrates application of methodology, but does not attempt a definitive analysis. This report is not concerned with the reassessment of risks from radiation exposure.

The goals of this report are to frame the problems, communicate the elements of the complex technical processes and methods of analysis, and provide a basis for more informed governmental decision-making and public participation in the issues.

The need to measure benefits, risks, and costs that include subjective values and are subject to pluralistic social values adds greatly to the difficulties of health benefit/cost analysis.

Many investigators have made monetary estimates of the value of life, of the biological damage caused by radiation exposure, of the expenditure justified to avoid a given radiation exposure, of the value of a man-rad, or of the value of a unit of risk to a life. There has been no internally consistent, theoretically justified conceptual basis for these studies, and although there has been some consistency among the estimates based on various premises, they must be viewed with some skepticism. Whether the method is acceptable is a question for consideration along with the question of alternative approaches.

Chapter III of this report presents an exposition of conventional economic benefit/cost analysis on the assumption that data are available where required. This exposition brings to light many problems in an analysis of activities in which radiation is produced. Radiation is considered in three major contexts: 1) its use in medical and dental diagnosis; 2) its use in medical therapy; and 3) its production in various stages of the nuclear fuel cycle. Each of these situations is different, and examples from all of them are utilized in illustrating basic concepts of benefit/cost analysis.

In some situations, one economic strategy may so dominate all others that there may be no need for valuing health or illness in monetary terms. However, more extensive analysis is usually required, leading to the need to find a common unit, e.g., monetization, for very elusive values. Also, inequities may arise, e.g., the cost may be borne by a segment of the population which does not share equally in the benefits. Another serious distributional problem relates to intergeneration effects: oil used today for the benefit of the present population may impose increased cost on unborn generations; dangerous long-lived radionuclides produced today for a present benefit will be a cost to future generations. When standard discounting procedures are used, future generations and their welfare are largely ignored.

A special problem is irreversibility. In conventional benefit-cost analysis, decisions are assumed to be reversible. Such is not the case in many aspects of benefit-cost analyses involving radiation and alternative modalities. For example, this occurs both in the case of production of long-lived dangerous nuclides by nuclear reactors and in the burning of irreplaceable fossil fuels.

Improbable but serious accidental events pose another problem in analysis. Melt-down of a nuclear reactor would be an example of this, and it is shown that a special type of analysis is required for this situation.

It is also shown that when the costs of a new program are very high and when its benefits are uncertain, conventional benefit-cost analysis may undervalue the health and social costs.

A fundamental assumption of conventional benefit-cost analysis is that human welfare (which benefit-cost analysis seeks to maximize) may be measured in monetary or materialistic terms. This assumption has fundamental problems. The materialistic system may not be the best one; for instance, it cannot handle the situations in which the risks and benefits do not accrue to the same people.

Benefit-cost analyses in the health field tend to be filled with many uncertainties and intangibles and to raise moral issues. Some people feel that such analyses should not be attempted at all since they appear to equate dollars with human lives. Other people feel that benefit-cost analyses, in spite of their obvious shortcomings, can assist governmental agencies and other public institutions in arriving at a rational allocation of resources and personnel.

Irreversible processes, quality of life, risk avoidance, distributional effects, incommensurability, and ethical considerations are not adequately addressed in conventional benefit-cost analysis. Therefore, under these conditions, conventional benefit-cost analysis cannot provide an exclusive basis for decision-making.

Chapter IV of this report reviews and assesses the efficacy of benefit-cost analysis for purposes of decision-making in the regulatory agencies, i.e., in the context of administrative and judicial decision-making on the control of the harmful externalities of such regulated activities as energy production.

The regulatory process is a relatively obscure one for most citizens. It is remote in spatial and emotional terms, is complicated and is not readily amenable to public understanding and participation.

The questions about the uses of benefit-cost analysis in the regulatory process which have been raised in this report are significant in that they relate to societal capacity to protect human health and welfare now and for the future generations which will bear the risks resulting from contemporary decisions on radioactivity and other harmful substances.

In the regulatory process, the only apparent alternative to conventional benefit-cost analysis has been cost-effectiveness analysis. As discussed in this report, cost-effectiveness analysis requires the articulation of objectives, the weighing of the alternative means to achieve the various articulated objectives, and the selection of the least costly approach. For regulation of nuclear energy sources of radioactivity, use of the cost-effectiveness approach would entail the establishment of societal health objectives and risk parameters (e.g., carcinogenic risks) by legislative or other institutional processes which are deemed acceptable as being socially representative.

The task of making such decisions on health objectives is certainly a difficult one but, once accomplished, the results may serve to ensure that regulatory decision-making on energy production and other activities involving harmful externalities is accountable with respect to articulated societal objectives for environmental health. This process would additionally force consideration of our stewardship for future generations. Consideration of alternatives to conventional benefit-cost and cost-effectiveness analyses for regulatory decision-making is perhaps the most critical need of the times from the standpoint of human health and survival.

One of the purposes of benefit-cost analysis of radiation uses is the practical one of providing a rational basis for decision-making in the field of radiation protection. It is hoped that this report may assist regulatory agencies in carrying out missions in the environmental protection field. It may assist agencies in decisions as to how best to allocate resources and personnel in order to keep unnecessary exposure of the public to ionizing radiation to a minimum.

A key element in the benefit-cost analysis of alternative strategies for energy development or for other applications of radiation must include the immediate and long-term costs of regulation and compliance, as well as the research costs underlying the development of standards and protection guides.

Another element of cost underlying various energy development strategies, not often explicitly examined nor generally equivalent for all options, is the cost of research and development assumed by all levels of government. When these costs are not distributed to the users, a subsidy exists for that option which must be accounted for in the benefit-cost analyses.

Benefit-cost analysis in nuclear power production is discussed in Chapter V. In applying benefit-cost analysis to nuclear power production, the proper comparison is with an alternative, such as fossil-fuel power production. The externalities associated with both technologies must be included in the analysis, in relation to all stages of both the nuclear and fossil fuel cycles.

Benefit-cost analysis can be applied effectively to nuclear power production at the level of technical decisions. However, where national policy is involved, decisions must inevitably be made on the basis of value judgments, to which economics, including benefit-cost analysis, can make only a limited contribution.

Models for benefit-cost analysis for medical and dental uses of radiation are developed in Chapter VI. The ethical considerations relating to radiation protection are placed in the perspective of current patterns of medical practice in the United States. The models developed are based primarily on the economic cost of illness and are designed to achieve a benefit-cost relationship. The models are general and imprecise. Unifying simplicity is achieved by monetization of benefits and costs and by relating the costs to the benefits to be derived by the individual and society as a whole. The prevention of disease and the failure to cure existing ill-health are considered in terms of the gain or loss of human resources. The reduction of radiation risk is considered as a means to achieve improvement in the benefit-cost ratio. The reduction-of-risk model is developed using a reduction-of-dose method; means to achieve this without impairing potential benefits of medical radiation are described. An approach to the development of alternative technologies and methodologies is considered briefly.

RECOMMENDATIONS

1. Development of national policies and strategies involving such activities as nuclear power production and medical uses of radiation and their alternatives, should be guided to the extent possible by health benefit-cost analyses. It should be recognized, however, that such analyses can only determine choices at technical levels where the technical information is available and cannot dictate choices or replace the ultimate responsibility of the decision-maker at higher levels where policy decisions must inevitably include more value judgments.

2. Regulation of radiation emissions from a source (e.g., nuclear power plant) based on benefit-cost analysis should include consideration of foreseeable and estimatable environmental and health effects of the pollutant off-site and over time.

3. The health and environmental effects of such pollutants should be considered by all interests including non-developmental or non-promotional interests, and limitations or parameters publicly established as to the permissible levels of such effects. Such limitations or parameters should be used in the benefit-cost analysis guiding the setting of control standards.

4. Conventional benefit-cost analysis, when extended along the lines we suggest in this report, would prove of some value, though limited, in assessing the relative merits of specific uses of radiation and alternative options, particularly at the technical level; for example, nuclear vs. fossil fuel cycles for energy production. Other factors, such as ethical considerations, will also need to be taken into account in the decision-making process.

5. Research efforts leading to the assignment of weighting factors to the elements of benefit-cost analysis which currently may be undervalued by marketplace economics, in comparison with societal value judgments, are recommended as an approach toward overcoming shortcomings of conventional benefit-cost analysis.

6. Careful study and appraisal of the benefits, risks, and costs to society and the individual of medical applications of radiation should be undertaken to provide the data required for the extensive benefit-cost analyses which could serve to guide the process of decision-making in diagnostic applications of radiation.

7. Careful benefit-cost analysis should be conducted to the extent possible as a guide in decisions as to whether or not to undertake mass x-ray screening programs of large populations in comparison with other alternatives.

The Committee urges that there should be a concerted effort to improve the benefit-cost ratio in medical applications of radiation, without limiting the benefits derived from modern radiological services. The largest current source of controllable man-made radiation exposure, by a factor greater than 10, is medical x-rays. Some exposures are of doubtful or no value to the individuals exposed. It would appear that the most significant and cost-effective reduction in the radiation exposure of the population as a whole is likely to be achieved by the development of methods of eliminating medically unproductive x-ray exposures.

To improve the benefit-cost ratio in relation to radiation exposure from nuclear energy production and to improve the data base for benefit-cost analysis of alternative technologies, the Committee urges the following activities:

(a) Improved training of protection personnel;

(b) Education of operators and users of energy sources and medical devices in sound personnel protection practices;

(c) Animal research directed toward investigation of dose-response relationships for genetic and somatic effects of various types of energy-production pollutants as a basis for rational comparison of all pollutants and the setting of standards;

(d) Epidemiological studies of people exposed to various levels and kinds of energy-production pollutants; and

(e) Continuing research in the development of improved protection methodology and procedures.

CHAPTER I

INTRODUCTION

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Chapter I

INTRODUCTION

A. The BEIR Report Of 1972

In its Report (The BEIR Report) of 1972, on "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation" (1), the NAS-NRC Advisory Committee on the Biological Effects of Ionizing Radiations estimated radiation risks, but did not deal with the methodology of benefit-cost analysis. That Report stated: "We need standards for the major categories of radiation exposure, based insofar as possible on risk estimates and on benefit-cost analyses which compare the activity involving radiation with the alternative options. Such analyses, crude though they must be at this time, are needed to provide a better public understanding of the issues and a sound basis for decision. These analyses should seek to clarify such matters as: (a) the environmental and biological risks of given developments, (b) a comparison of these risks with the benefits to be gained, (c) the feasibility and worth of reducing these environmental and biological risks, (d) the net benefit to society of a given development as compared to the alternative options."

"In the foreseeable future, the major contributors to radiation exposure of the population will continue to be natural background with an average whole-body dose of about 100 mrem/year, and medical applications which now contribute comparable exposures to various tissues of the body." (See Table I.1 for sources and amounts of radiation exposure.) "Medical exposures are not under control or guidance by regulation or law at present. The use of ionizing radiation in medicine is of tremendous value but it is essential to reduce exposures since this can be accomplished without loss of benefit and at relatively low cost. The aim is not only to reduce the radiation exposure to the individual but also to have procedures carried out with maximum efficiency so that there can be a continuing increase in medical benefits accompanied by a minimum radiation exposure."

"Concern about the nuclear power industry arises because of its potential magnitude and widespread distribution. Based on experience to date and present engineering judgment, the contribution to radiation exposure averaged over the U.S. population from the developing nuclear power industry can remain less than about 1 mrem per year (about 1% of natural background) and the exposure of any individual kept to a small fraction of background provided that there is: (a) attainment and long-term maintenance of anticipated engineering performance, (b) adequate management of radioactive wastes, (c) control of sabotage and diversion of fissionable material, (d) avoidance of catastrophic accidents."

The BEIR Report indicated that to the extent that existing guidelines and medical radiation exposures can be reduced without impairing benefits, the exposures are unnecessarily high. As recommended by the NCRP (2), such radiation exposures should be kept "as low as practicable" below recommended numerical limits.

TABLE I.1

Summary of Estimates of Annual Whole-Body Dose Rates in the United States (1970)

Source	Average Dose Rate* (mrem/yr)	Annual Person-Rems (in millions)
Environmental		
Natural	102	20.91
Global Fallout	4	0.82
Nuclear Power	0.003	0.0007
Subtotal	106	21.73
Medical		
Diagnostic	72**	14.8
Radiopharmaceuticals	1	0.2
Subtotal	73	15.0
Occupational	0.8	0.16
Miscellaneous	2	0.5
TOTAL	182	37.4

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* Note: The numbers shown are average values only. For given segments of the population, dose rates considerably greater than these may be experienced.

** Based on the abdominal dose.

From the BEIR Report (1972). (Ref. 1)

Some of the recommendations of the BEIR Report are concerned directly with the task of the present Committee, i.e., benefit-cost analysis. In this regard the Report stated: "It is not within the scope of this Committee to propose numerical limits of radiation exposure. It is apparent that sound decisions require technical, economic and sociological considerations of a complex nature. However, we can state some general principles, many of which are well-recognized and in use, and some of which may represent a departure from present practice." (Quoted below are those "principles" closely concerned with benefit-cost assessment.)

"a) No exposure to ionizing radiation should be permitted without the expectation of a commensurate benefit.

b) The public must be protected from radiation but not to the extent that the degree of protection provided results in the substitution of a worse hazard for the radiation avoided. Additionally there should not be attempted the reduction of small risks even further at the cost of large sums of money that spent otherwise, would clearly produce a greater benefit.

c) There should be an upper limit of man-made non-medical exposure for individuals in the general population such that the risk of serious injury from somatic effects in such individuals is very small relative to risks that are normally accepted. Exceptions to this limit in specific cases should be allowable only if it can be demonstrated that meeting it would cause individuals to be exposed to other risks greater than those from the radiation avoided.

d) Medical radiation exposure can and should be reduced considerably by limiting its use to clinically indicated procedures utilizing efficient exposure techniques and optimal operation of the radiation equipment. Consideration should be given to the following:

    1) Restriction of the use of radiation for public health survey purposes, unless there is a reasonable probability of significant detection of disease.

    2) Inspection and licensing of radiation and ancillary equipment.

    3) Appropriate training and certification of involved personnel.

e) Guidance for the nuclear power industry should be established on the basis of benefit-cost analysis, particularly taking into account the total biological and environmental risks of the various options available and the cost-effectiveness of reducing these risks. The quantifying of the 'as low as practicable' concept and consideration of the net effect on the welfare of society should be encouraged.

f) In addition to normal operating conditions in the nuclear power industry, careful consideration should be given to the probabilities and estimated effects of uncontrolled releases. It has been estimated that a catastrophic accident leading to melting of the core of a large nuclear reactor could result in mortality comparable to that of a severe natural disaster. Hence extraordinary efforts to minimize this risk are clearly called for."

B. The Task Of The Present NAS-NRC Advisory Committee

The task proposed by the Environmental Protection Agency (EPA) and accepted in principle by the present NAS-NRC Advisory Committee on Octobe. 18, 1973, is specified below in detail.

"The Director, Criteria and Standards Division, Office of Radiation Programs, Environmental Protection Agency, has requested that the National Academy of Sciences investigate the problem of evaluation of the total benefits derived from exposure to ionizing radiations for comparison with the total risks. This study is intended to complement the recently completed study on reassessment of biologic risks associated with low level exposure to ionizing radiation. This study will include considerations of benefits and risks of options alternative to radiation exposure, as well as any benefits and risks associated with radiation exposure, especially as they place the benefits and risks of radiation exposure in perspective for guidance and for public understanding."

"To perform the comparative evaluation of benefits and risks the Advisory Committee on the Biological Effects of Ionizing Radiations would:

1) Review and evaluate benefit assessment techniques that may be available.

2) Develop benefit/risk assessment methods which will be useful in performing comparative studies of benefits and risks from activities involving exposure to ionizing radiations.

3) Apply the techniques where possible.

4) Evaluate associated factors of benefits and risks in ways that could be used in the establishment of reasonable protection guides."

"The BEIR Committee would include in its membership for this purpose persons from social, economic, legal, technological fields, etc., as well as persons from the more directly related areas of sciences."

"The categories of benefits which might be considered, among others, are: 1) survival and health, 2) security, and 3) self-gratification or other life quality factors, i.e., any factors which could provide a framework for arriving at measures of benefits relative to risks or costs."

"The end-point or goal of such a study would be primarily the devising of methods of balancing benefits and risks, which could and would then be applied to various categories of radiation usage."

To carry out the required review and analysis, three subcommittees were formed to deal with the following subject areas: 1) concepts, 2) energy production, and 3) medical applications.

C. General Approach In The Present Report

The main categories of radiation exposure or usage considered in this report in regard to the principles of benefit-cost analysis are energy production and medical applications of radiation. These are the most important with respect to peaceful man-made radiation exposure of the population currently (medical radiation) or potentially (nuclear power generation), and with respect to their potential benefits. They also represent situations requiring substantial differences in modeling, benefit-cost alternative factors, and analytical problems.

The general approach in this report includes consideration of the following: concepts of benefit-cost analysis; available assessment techniques and processes; conditions and agents positive and negative to health, life expectancy, and quality of life in regard to radiation usage or exposure and to feasible alternatives; distribution of these positive and negative conditions and agents and their effects spatially and temporally with respect to population; regulations governing deleterious agents; ethical principles; effects in terms of benefit versus risk; conversion of quantified benefit parameters and risk parameters into common units, e.g., monetary units, for overall analysis and comparisons of benefit and risk; and risk perception and acceptability.

The goals of the report are to frame the problems, communicate the elements of the complex technical processes, and provide a basis for more informed public participation in related issues. In the present state of severely limited quantitative knowledge pertinent to many of the essential elements of this highly complex problem, it is not now possible to provide a comprehensive and definitive, and therefore completely persuasive, analysis in this Report.

CHAPTER I

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CHAPTER II

NEEDS, PROBLEMS, AND APPROACHES OF THE TIMES

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CHAPTER II

NEEDS, PROBLEMS, AND APPROACHES OF THE TIMES

A. Needs and Associated General Problems

In discussing needs of the times, the BEIR Report (1) states: "When the risk from radiation exposure from a given technological development has been estimated, it is then logical for the decision-making process that comparisons be made and consideration given to a) benefits to be attained, b) costs of reducing the risks, or c) risks of the alternative options including abandonment of the development. The concept of always balancing the risk of radiation exposure against the expected benefit has been well-recognized and accepted, but no serious attempt has been made to evaluate both sides of the equation in any way that could lead to operational guidance. Official recommendations call for radiation exposure to be kept at a level 'as low as practicable,' a policy that emphasizes and encourages sound practice. However, risk estimates and cost-benefit analysis are needed for decision-making. An additional important point, often overlooked, is that even if the benefit outweighs the biological cost, it is in the public interest that the latter must still be reduced to the extent possible providing the health gains achieved per unit of expenditure are compatible with the cost-effectiveness of other societal efforts."

"It appears logical to attempt to express both risks and benefits in comparable terms--dollars. To a limited degree risks can be estimated in such terms. For example, the statement of risk can be expressed in terms of cost to an individual or to his family and society since there are specific expenses attributable to an effect. Similarly, estimates can be made of expenses required to effect given reductions of exposure to harmful agents. In some instances, it may not be necessary to use absolute dollar costs: that is, one can compare the cost of different ways of producing the same desired objective. Given the need for additional electrical power, one might compare nuclear plants and fossil fuel plants directly in terms of total biological and environmental costs per unit of electricity produced. Often, however, there will be need for information on absolute costs. This will occur when decisions have to be made on whether the public interest is better served by spending our limited resources on health gains from reducing contamination or by spending for other societal needs."

"It must be emphasized that there are many inherent problems in cost-benefit analysis that will prevent rigorous application in the very complex systems of present concern to society. These include the implication of assigning a monetary value to human life, suffering or productivity; the difficulty in assessment of factors related to the quality of life such as recreational water and land resources; the fact that the costs and benefits may not accrue to the same members of the population, or even to the same generation and the virtual impossibility of establishing a single cost system that would be socially acceptable and still take into account differences in individual willingness to accept various types of risks. An illustration of the latter points is the observation that health and environmental effects from power plants would be reduced by their location in relatively unpopulated areas. Yet the people in such areas generally are not the ones who need the additional electrical energy."

"Despite these uncertainties, there are important advantages in attempting cost-benefit analyses. There is a focus on the biological and environmental cost from technological developments and the need for specific information becomes apparent. Thus, for example, we find relatively little data available on the health risks of effluents from the combustion of fossil fuels. Further, it is becoming increasingly important that society not expend enormously large resources to reduce very small risks still further, at the expense of greater risks that go unattended; such imbalances may pass unnoticed unless a cost-benefit analysis is attempted. If these matters are not explored, the decisions will still be made and the complex issues resolved either arbitrarily or by default since the setting and implementation of standards represent such a resolution."

"We now come to an important area that requires newer approaches. It is suggested that numerical radiation standards be considered for each major type of radiation exposure based upon the results of cost-benefit analysis. As a start, consideration should be given to exposures from medical practice because of present relatively high levels of exposure and from nuclear power development because of future problems of energy production and the need for public understanding."

"With the development of modern health care programs in the Western world, there has been a marked increase in the use of radiation in the healing arts--medical diagnostic radiology, clinical nuclear medicine, and radiotherapy. This has resulted in the recognition that medical radiation now contributes the largest fraction, by one or two orders of magnitude, of the dose from man-made radiation to the United States public." "The significance of this lies in the absolute reduction of exposure that could be brought about at relatively low cost with no reduction in medical benefit...."

"The difficulties in attaining a useful cost-benefit analysis for nuclear power are formidable and will require interdisciplinary approaches well beyond those that have yet been attempted. Areas that require evaluation include: a) projection of energy demands, b) availability of fuel resources, c) technological developments (clean combustion techniques, coal gasification, breeder reactors, fusion processes, magnetohydrodynamics, etc.), d) public health and environmental costs of electrical energy production from both nuclear and fossil fuel including aspects of fuel extraction, conversion to electrical energy, and transmission and distribution."

Society now has the task of reducing the population exposure to hazardous agents, such as radiation and the pollutants from fossil-fuel combustion, to levels as low as practicable or readily achievable, and must know where to stop and where and how to allocate its limited resources for health protection and safety to obtain the best yield in reduced risk from activities providing public needs and benefits. The further the process of risk reduction goes the higher the cost per unit of risk reduced, and eventually a level is reached where a further reduction is prohibitive and unjustified.

Implicit in the attempts of society to eliminate unnecessary exposures or risks is the application of some form of cost-benefit analysis. Particularly in the area of health and safety, the government is making, and the public is demanding, an increasing number of preemptive decisions that involve, or should involve, an analytical process for decision-making capable of evaluating immediate and potential risks and costs and of balancing social benefits.

In attempting to establish an analytical methodology of decision-making, some of the most basic questions and problems are concerned with how people would measure and make judgments of the utility or attractiveness of various activities, how people would measure and judge the probability of events that can affect them, how judged probabilities would be changed in accordance with the arrival of new information, and how measured and judged utilities and probabilities could be quantified in comparable or common units and combined for input to decisions.

A major philosophical question for decision is whether or not there exists an unacceptable risk, in the sense that when the hazardous consequences of a particular event stemming from a development or activity reaches a certain magnitude it becomes unthinkable to allow even the most remote possibility of that event occurring. If a risk were determined to be unacceptable, it would be necessary either to design the development to make the event impossible, or to forego the benefits and abandon the development or activity. This concept places an infinite value on risks of the size under consideration. On the general question of risks that may be regarded as unacceptable regardless of the probability of occurrence, a Committee on Public Engineering Policy (COPEP) Report (2) indicates that COPEP "believes that risks and benefits must be regarded as a continuum, and incremental changes across the whole range must be part of the analysis."

In performing decision analyses, there is a tendency to concentrate on those aspects that are easier to treat, such as those involving quantifiable, commensurable variables, and to neglect the more subtle or subjective variables involving psychological factors, quality of life, aesthetics, loss or gain in personal freedom or privacy, etc. Also, it is difficult to represent the concerns of people in a manner compatible with the balance of the analysis. There are problems of dealing with different ethics and values, problems of dealing with present versus future generations, problems of ascertaining what people are willing to pay for certain benefits, problems of dependencies among different values, the problem of acceptability of alternatives in the context of possible future shifts in values, and other problems of interaction.

Traditionally, benefit-cost ratios in engineering planning and design have been the province of economists who dealt with the monetary costs of projects in relation to expected performance, savings or profits. Benefit-cost analysis now often refers to an evaluation of all of the benefits and the costs of a proposed activity, and includes also benefit-risk analysis in which risks to life and health are an important component of the consideration of costs. This greater comprehensiveness makes the analysis more difficult and perhaps for the time being less definitive.

Starr (3) has pointed out that society's historical empirical approach to arriving at acceptable balances of technological benefit and social cost, by trial, error, and subsequent corrective steps, creates in advanced societies today a critical situation, for two reasons: 1) the difficulty in changing a technical subsystem once it has been woven into the economic, political, and cultural structures; and 2) the techniques for societal diffusion of a new technology and its subsequent exploitation are now so highly developed that widespread use of a new technological development may occur before its social impact can be properly assessed, and before any empirical adjustment of the benefit-versus-cost relation is obviously indicated.

Only recently have the administrative and technical tools enabling possible comprehensive, quantitative and practical benefit-cost analysis become available. There has been increasing application of benefit-cost analysis and benefit-risk analysis in assessment of technology. As part of this process, the side effects and long-range consequences may be evaluated along with the more immediate, obvious and direct consequences.

Although such analyses, as they become increasingly more comprehensive and accurate, will be of increasing usefulness to decision-makers in choosing between alternative technical approaches to solve societal problems and in allocation of societal resources, they do not alone determine how much technology of one or another kind a society can justifiably purchase.

There are many independent factors, ranging from the scientific to the political, in benefit-cost analysis, in the subsequent decision-making and in the setting of protective safety standards for technological activities.

Health scientists, acting only in their roles as scientists, are concerned with the development and correctness of knowledge and evaluation of the health effects of the technological activity. The political representatives of society receiving scientific, technical, and political information are concerned with the costs and the extrinsic values that society assigns to the effects and with the exercise of wisdom in decision-making concerning a value acceptable for society for the effects in relation to the benefits of the activity.

Because of the inadequacies of currently available data on certain effects and their mechanisms, and in some cases the possible existence of as yet unknown effects, biomedical scientists are currently limited in the degree to which they can meet public expectations. For this reason, accurate assessment of health costs for use in setting standards requires a substantial research effort.

The prime motivation for establishing protection standards for the public is political, i.e., the general public, through its formal institutions, defines the goals and promulgates the rules. Society's political institutions give the authority and responsibility for establishing acceptable standards to the standards-setters who must evaluate the costs of pollution and balance them against the costs of abatement, i.e., translate the biological effects or risks into societal costs.

Currently, electromagnetic radiations are covered by federal laws either related to the Atomic Energy Act, as amended, or to the Radiation Protection Act of 1968. Through these laws, the federal government can regulate ionizing radiation emissions from nuclear processes and natural radioactive materials, as well as ionizing and non-ionizing radiation generated by machines. The National Environmental Policy Act of 1969, as implemented by the Council for Environmental Quality, specifically requires government agencies to consider alternatives to proposed actions affecting the environment and requires environmental impact statements from those proposing developments which may affect the environment. There is increasing need and awareness of the government's responsibility to take into account the benefits and risks associated with program decisions, consumer demands, new regulations concerning efficacy and safety. The National Environmental Policy Act requires governmental agencies to study and publish evaluative statements prior to the making of project decisions with significant environmental impact.

B. Problems of Risk Estimation, Perception and Acceptance

The deleterious side effects of technological activities or pollutants on health may range from the probable occurrence of slight harm to the improbable occurrence of severe harm, and range widely from minor discomfort to violent death, from transitory to permanent, from localized to worldwide. The deleterious agents may be chemical, physical, or biological, of naturally occurring types increased above natural concentrations or synthetic types more easily identified, from obvious or obscure sources. The relationship between the deleterious agents and their resultant health effects may be obvious and recognized immediately, especially those effects which follow soon after exposure (acute effects), or more obscure, such as those effects occurring long after brief exposure, or as a result of long low-level chronic or intermittent exposure. Careful epidemiologic analysis may be needed to reveal increased frequency of an otherwise naturally occurring effect in the exposed population.

There can be considerable individual variation in response to radiation and the various other pollutants, such as those from fossil fuel energy production, of concern as subjects of this report. The individual variations in response relate to stage of development or age, clinical condition, sex, and genetic constitution.

The somatic health effect of exposure to pollutants that is probably of greatest public concern is cancer. Radiation and various environmental chemical pollutants are known to be carcinogenic. One of the difficulties in evaluating carcinogenic potential of low levels of radiation and chemical environmental pollutants in human beings is the long latent period between exposure and development of cancer. Another problem is related to the possibility of additive or synergistic effects among agents which individually may be weakly carcinogenic at the environmental levels of concern and difficult to identify. Ionizing radiations from external sources and radionuclides are used in medical applications and are pollutants from nuclear energy power production. The classes of carcinogenic agents identified so far as being present in products of fossil fuel combustion are polycyclic and other aromatic hydrocarbons, trace metals, and radionuclides.

Genetic effects, i.e., those occurring in the progeny of the exposed persons, are caused by a class of agents called mutagens. Ionizing radiation and various chemical pollutants are mutagenic. Mutational changes vary in severity from subtle changes of negligible consequence for health to lethal effects. Owing to uncertainty as to how genetic effects of deleterious agents in the environment will be expressed and recognized, accurate quantification is difficult if not impossible. However, because of the extensive experimental research done on the genetic effects of ionizing radiation, it is possible to predict roughly by extrapolation the possible types and numbers of effects that might be caused in human populations from increased levels of radiation.

There is a dilemma in attempts to assess the health effects of low levels of a pollutant in large populations when the pollutant is known to be harmful only at higher levels. After radiation came to be known as harmful at high levels and, as a result of nuclear weapons testing and extremely sensitive means of detection of radioactivity, it was found that many living organisms throughout the world contained detectable amounts of man-produced radioactivity, such large amounts of money and manpower were spent for research on this potential source of harm that probably much more is known about the effects of ionizing radiation than about the effects of other agents to which man is exposed. More recently, sensitive measures have been developed for various chemical pollutants, including those from fossil fuel combustion, in the biosphere that could be potentially harmful, so that now there is concern and pressure to eliminate completely or greatly reduce the possible health risks from these agents.

There is a need for better public understanding of the problem, the relationship between the level of a harmful agent and its potential effects, and the virtual impossibility of eliminating all potential risk from most activities.

For any deleterious agent, there is a range of high levels which are lethal and cause death early in a large proportion of the exposed population. Below that range is a range of levels causing observable acute signs of effect but with a lesser incidence of early death, if any. These acute clinical effects may disappear and not necessarily be long-term contributors to ill health, or may be indicative of high probability of serious late effects. At still lower levels of the deleterious agent, early or late effects of various kinds may be difficult or impossible to detect definitely by current methods in human populations, either because they are minor or subtle or if serious occur late and with very low frequency. If the probability or risk of such serious late effects is suspected or perceived to be high enough, society may consider the risks intolerable. Enough is known about ionizing radiation that risk levels in this range can be specified. Within the present guideline levels for radiation protection, no serious health effects have been observed in exposed populations, clinically or epidemiologically, although on the basis of radiobiological theory it is postulated that such effects could occur. At some low levels for any deleterious agent, the probabilities of effects may be so low that society is willing to accept them and is justified in this acceptance if the effects are more than compensated by the associated benefits of the activities that produce the agents.

The understanding of risk, and the problem of risk acceptance, in regard to low levels of various pollutants, requires an understanding of the distinction between two types of agents, those with a dose "threshold" for effect and those with no dose threshold for effect ("non-threshold"). For "threshold" agents, there is some level below which the agents do not cause a specified effect. For "non-threshold" agents, there are certain specified effects which occur in some incidence as a consequence of any level of the agent. Regulatory procedures and standards that presumably guarantee absence of risk can be set for threshold agents. However, for non-threshold agents, there must be acceptance of some level of risk unless the agent can be eliminated completely. To obtain the benefit of an activity which produces a deleterious agent, and at the same time minimize the risk to the public as much as possible in relation to the worth of the benefit, it is desirable to establish regulations limiting population exposure to the agent at some appropriately low level. For this purpose, it is important to gain knowledge of the mathematical relationship between level of exposure and incidence of serious effects, and the actual or at least the probable nature and slope of this relationship in the range of exposure levels of interest, so that public acceptance of certain levels of risk commensurate with associated benefits can be recommended.

In considerations of health risks of technological activities, severe disability and premature death have been emphasized because they are the most important effects and because it is difficult to quantify and evaluate meaningfully many of the less serious effects. Even these serious effects are variable in their impact on individuals and society, e.g., in regard to age at the time of occurrence, societal responsibilities, productivity, etc. At present, it is not possible in the formulation of risks and costs to estimate the number of person-years lost because of exposure to the agent or to weigh them to account for societal and personal impacts.

On the other hand, it is possible that morbidity and disability may have even greater impact on societal welfare than premature death in some respects. Although mortality data are most readily available and quantifiable, they are at best only indicative of the total risk, such that the total social cost would be better approximated by application of a factor for associated disabilities. Furthermore, mortality or disability expressed as incidence alone, unless converted to amount of life-time lost or duration of disability, by accounting for age at occurrence, are not fully indicative of individual loss or societal cost. The time required for disability and death to occur as a result of exposure to various pollutants may vary greatly depending upon the pollutant, the degree and intensity of exposure, and the age at exposure. The factors of age-related incidence of mortality, lifetime lost, age-related incidence and degree and duration of morbidity or disability, age at exposure, changing social values as a function of age, and other like public health parameters are parts of the full evaluation of social costs theoretically and practically. However, owing to the current inadequacy or uncertainty of relevant data for such complete analysis, evaluations in terms of orders of magnitude are usually the best that can be expected.

Historically, there are many examples of benefit-cost analyses that have been determined empirically; for example, society has evidently decided that the benefits of automobile and airplane travel outweigh the risks and economic costs. The fact that the social benefits from these and some other voluntary activities of the public can be estimated and that there are readily available historical data on accidents and health hazards for some of these types of public activities, has prompted various attempts at quantitative evaluation of such types of social cost.

A complication in assigning risk or cost values statistically is that risks may be borne by some persons disproportionately in relation to their share of the associated benefits. However, in situations involving allocation of risks involuntarily to the public, in which a relatively large proportion of the population is affected by the proposed activity and the maximum risk to any population subgroup or individual is sufficiently small, the risk-cost distribution may reasonably be regarded statistically, even when risks and benefits are assumed disproportionately by different groups of people.

The values that have been least well considered, defined or quantified in benefit-cost evaluations are those for human life (e.g., mortality, disability, discomfort) and aesthetics. The quantitative benefit-cost evaluation implies the willingness to accept a certain level of risk of death or injury in exchange for a sufficiently large benefit, biological or financial or other. This also implies willingness to place a tangible value on human life. Such value judgments are routine in our society. Directly or indirectly, society is constantly setting and adjusting monetary values for human life, disability and discomfort, for example, jury or court awards of financial settlements, in actuarial or insurance measures and in premium pay for hazardous occupations. This concept is needed and useful practically as a tool and common comparable unit in benefit-cost analyses and as a reflection of a method society already uses, with the understanding that this use of monetary values only indicates rather than summates some values of human life and does not imply insensitivity to the concept that individual life is priceless.

Data and estimates on deaths from induced cancer could be converted to figures reflecting life-span lost. The economic costs to society, both in terms of increased cost of medical services and loss of productivity, as well as the economic losses of those persons more directly affected could be estimated for cured and non-cured induced cancers. Also, estimates on increases in ill-health due to genetic effects could be converted into economic costs. Such conversion of the risk estimates to dollar figures would make possible the adding of genetic and somatic effects in a common unit to facilitate a general benefit-cost analysis.

Several investigators have made monetary estimates of the biological damage caused by exposure to ionizing radiation or the expenditure justified to avoid a given radiation exposure: these estimates range from less than $100 to many hundreds of dollars per man-rad of radiation dose. The consistency of such estimates from various sources suggests that, in the broadest area of making benefit-cost analyses, the formulation of these difficult value judgments is within the realm of possibility. Whether this method is acceptable is a different question which must be faced along with the question of alternatives.

The actual cost to society of a radiation-induced illness or death goes beyond the monetary payments made to survivors, hospitals, etc., since the value of life and health is also involved. The value of life and health to the individual who is the potential victim is different from its value to his relatives or to society. The dollar value of life and health is dependent in some way on the possible outcomes and probabilities associated with the level of risk. As an example of one aspect of this dependence, the value to society but not to the individual of an expected life from 30 to 70 years of age may be many orders of magnitude greater than that of living from 70 to 71 years.

The rational approach to dealing with risks is to measure risks and associated benefits and costs of options and to develop a method for making decisions on the optimal balance. It seems reasonable to anticipate that some readily quantifiable aspects of risk and benefit may be determined with increasing accuracy as more knowledge of relevant effects and their mechanisms accumulates. On the other hand, where important aspects of risk and benefit are highly subjective and cannot be readily quantified or evaluated, fully meaningful benefit-cost analysis or balance is impossible to achieve. To compare the presently subjective areas of benefit and risk would require establishment of a system of criteria of judgment and weighting.

Risk evaluation and risk-acceptability evaluation are two distinct problems. It is relatively easy to perform retrospective risk-acceptability evaluation by examining examples of public acceptance of levels of risk for various activities in relation to associated levels of benefits. Prospective risk-acceptability evaluation, i.e., to estimate the subjective values placed on future risks, is much more difficult.

The evident fact that the risk perspective of an individual may differ from that of a social group creates a problem in a democratic political system. Rational decision-making on a societal level may thus require an intensive public education and public discussion of the issues and trade-offs. This is particularly difficult in emotion-laden areas, and perhaps especially so when death, disability and discomfort of human beings are involved.

In regard to the psychological factors to be taken into account in dealing with the public and with the news media, one question is concerned with the use of absolute versus qualified statements on risk. In general, scientific statements require qualification, whereas there is a tendency for the news media, and the public also, to perfer categorical statements, usually in fairly extreme form. What may begin as well qualified simple and safe pragmatic assumptions by scientists for interpretation of human data may become transformed into unqualified dogma in communication to the public.

CHAPTER II

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CHAPTER III

CONCEPTS OF BENEFIT-COST ANALYSIS

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CHAPTER III

CONCEPTS OF BENEFIT-COST ANALYSIS

Summary

In this chapter is presented an exposition of classical economic benefit-cost analysis assuming that data are available where required. This illuminates many problems in an analysis of activities in which radiation is produced. Radiation arises in three major contexts: it is used for medical diagnosis; it is used for medical therapy; and it is produced during power production in atomic reactors. Each of these situations is different and examples from all of them are utilized in structuring a benefit-cost analysis.

It is shown that in certain cases a given strategy dominates, e.g., if both market-incurred costs and external costs (such as health effects or landscape degradation) are less than for an alternative, then the need for monetizing health or illness can be avoided.

In many cases, however, certain special problems arise. One of these is inequality in distribution of effects. The costs may be incurred by a segment of the population which does not enjoy the benefits. Another serious distributional problem relates to intergenerational effects. The oil used today for the benefit of the present population may mean an increased cost is distributed to unborn generations. Entirely analogous is the problem of dangerous long-lived radionuclides produced today for a present benefit which are a cost to future generations. If standard discounting procedures are used, the welfare of our grandchildren is largely ignored. Another special problem is irreversibility. This occurs both in the positive sense when long-lived dangerous nuclides such as plutonium are produced by atomic reactions, and in the negative manner when fossil fuels are burned since they cannot be replaced. In general, in classical benefit-cost analysis, decisions are assumed to be reversible from a societal standpoint. Such is not the case in many aspects of benefit-cost analyses involving radiation and alternative modalities.

Improbable but serious events pose another problem in analysis. Meltdown of a reactor is an example of this and it is shown that a different type of analysis is required for this situation.

Finally, it is shown that when the costs of a new program are very high and when its benefits are uncertain, standard benefit-cost analysis undervalues the health and social costs.

CHAPTER III

CONCEPTS OF BENEFIT-COST ANALYSIS

A. Introduction

Comparison of costs and benefits is as old as human comprehension. The decision of primitive man whether to go hunting or sleep when the larder is full is basically a weighing of the costs versus the benefits accruing to alternative actions. Modern industry is constantly involved in benefit-cost analyses and upon their accuracy depends the company's future. Most societies have sporadically made intuitive judgments in which costs have been balanced against benefits for alternative actions, where such actions may be war or negotiation, public benefit or private prosperity, present expenditure or present austerity. In the last few centuries some societies have been governed in part on the principle that the sum of the multitudinous individual assessments of personal benefits-costs will automatically yield a rational national welfare maximum. This more or less implicit assumption has usually been embedded in an economic system generally agreed upon in the culture. There is a tendency, however, for individual benefit-cost analyses to underestimate total costs by externalizing them. Production which allows pollution of air, water, or land transfers some costs to society at large, so that pollution is profitable for some individual businesses. Some societies have attempted centralized decision-making in which the general population has had (usually) a relatively small input into the analyses and subsequent decisions. General ideologies have frequently been of overriding consideration in such decisions.

Society, and in particular the United States, must now make difficult choices concerning the standard of living which we and our children and their heirs may achieve. The health and safety of the general population and the amenities of life including especially the physical and biological condition of the country and city, the land and water, also require decisions which are to a great extent dependent on our choice for the standard of living we expect. A society may have, and usually has had, the apparent opportunity to defer decisions. It is obvious that postponing a decision is in itself a decision and one that has as important and far reaching effects as making a decision. Nonetheless, there is a human tendency to avoid those decisions which leave a large fraction of the population dissatisfied no matter which alternative is chosen. Hence, in the past, deferral of difficult decisions has, perhaps, been more common than decisive action. Several circumstances have now converged to make societal decisions in the United States inevitable. These are: 1) the increased role of the government in regulation of industry. It is now not possible for many large industries unilaterally to make decisions unconstrained by governmental regulations; 2) the realization by the majority of the citizenry that the world's resources are finite and that consequences flow from this; 3) an increasingly informed and vocal population which has a certain amount of political influence and which is concerned with environmental protection, public safety, etc.

B. Scope

Given that decisions are required and that rationality demands analysis before decision, this section will be concerned with an examination of the process of benefit-cost analysis as it relates to ionizing radiation. This radiation affects society in a variety of ways. The effects of the radiation on living organisms are deleterious. It may kill, it may cause cancer, and it may cause genetic damage. An important feature of the radiation at low-dose levels is that the effects are random and are predictable only in a statistical sense. If 1,000,000 adults receive 100 rads of general body radiation, we can predict on the basis of certain assumptions that over a period of 10 years duration of risk about 2,000 of them will develop leukemia (1). We cannot, however, predict who will get leukemia and who will be spared. In special instances, therapeutic radiation can be used to destroy cancerous tissue and per se have a beneficial effect. In other instances, where radiation is used to visualize parts of the body for the purpose of diagnosis, the radiation although deleterious is required for the process of image formation. In still other situations, radiation is produced incidental to but inevitably as a result of some process. The prime example of this is radiation produced by atomic reactors. Each of these uses and sources of radiation has such different and special features that they will be dealt with separately. Moreover, some radiation is impossible to escape; everyone received from naturally occurring radioisotopes and cosmic rays and about 0.1 rad/year. For comparison, in the United States each person on the average receives about 0.07 rad/year from all medical use.

Increasing relative scarcity of traditional sources of energy is probable within the coming decades. Nuclear energy has the potential for providing civilization with energy for several centuries but with attendant unwanted radiation exposure. Hence, a document which deals with benefit-cost analysis for activities involving radiation exposure must consider energy sources and power production.

As seems evident from the foregoing and as will become clear later in this discussion as various problems are considered in greater detail, it is not possible, using the tools of benefit-cost analysis, to arrive at a formula which will describe the exact amounts of oil, coal, and nuclear fuels to be used each year. Nor will it be possible to have another formula which will advise us how much to spend for research in the various actual and potential energy supply systems such as coal, solar, geothermal, fusion, etc. However, economic and benefit-cost analyses, although difficult, could give guidelines for the optimal mix of different power sources for the United States for the next several decades, given certain assumptions. These assumptions fall into four categories and any attempt to formulate benefit-cost calculation must begin with assumptions derived from each of these categories.

1. The first category of assumption is concerned with irreversible processes. These are of two types which have certain symmetrical features. Depletion of oil is not only irreversible but given the fact that United States oil production reached its peak several years ago, the exhaustibility of oil resources is a problem of

immediate concern. Equally irreversible is the accumulation of radioactive wastes from nuclear power stations. This generates problems in handling and in storage which can only be a burden on future generations. This special feature of irreversibility is of critical importance and different qualitatively from most parameters usually considered in benefit-cost analyses. Although science and technology can offer some guidance, value judgments are required as to the relative importance of depleting one resource versus providing an unwanted burden of radiation exposure from radioactive wastes.

2. The time frame of the analyses is an important assumption. Does one optimize the proportional share of different energy sources for ten years or for 100 years? Clearly the results will differ if we wish to spend energy profligately now or conserve it. An ancillary but important consideration in this regard is the relationship between discoveries or inventions and the level of energy availability in an economy. It seems likely that a technologically advanced society will require more energy but will also be more likely to discover new ways of producing substitutes for oil or using or rendering less dangerous the radioactive wastes.

3. Another vital assumption necessary for any calculation is the assumed level of energy consumption over whatever time span is decided in the second assumption. An energy intensive economy will produce more wastes and deplete more oil than will an economy with a static or decreasing consumption of energy.

4. A final assumption involves a value judgment about the quality of life, a term difficult to define precisely and subject to difference of opinion; for example, can the value of the energy produced from coal or nuclear power plants be weighed against the ecological and aesthetic qualities? Naturally, there is no uniformity of opinion as to even what is aesthetically pleasing and what is not.

These general considerations will be discussed in various parts of this document.

In this chapter, we shall consider certain general mathematical statements which are required for benefit-cost analysis. In this exercise, we shall examine some unusual problems which arise. Paramount among these are incommensurability among variables and inequalities in both temporal effects and between those individuals who receive benefit and those who suffer damage. These inequalities must be identified and segregated so that comparisons may be made of functions or numbers having the same dimensions. In most analyses, political and human factors enter into the construction of a method of benefit-cost analysis. The difficulties, ambiguities and frequently almost arbitrary assumptions inherent in most complex benefit-cost analyses concerning radiation are so large that in a democratic society, public input into some of these assumptions would appear to be required. It is conceivable that an analysis could be performed in such a way that assumptions are hidden and arbitrary decisions about the value of human life and suffering concealed, so that the results of an arcane formulation are presented to both decision-makers and the public as an unarguable conclusion. The basic tenets of a democratic society preclude this manner of decision making. Hence, we propose to consider those aspects of benefit-cost analysis in which judgments of both an ethical and political nature are involved. Additionally, we hope to examine from an historical or precedental aspect how these judgments may properly be exposed to public appraisal and possible preliminary decisions made. This review of analysis will demonstrate that in a certain sense benefit-cost analysis which involves radiation is a stepwise process in which various sectors of public opinion may be involved at several discrete points. This implies that there is not one analysis to be presented to one decision-making body, but that during the process there are multiple stages at which decisions of a non-scientific nature are required.

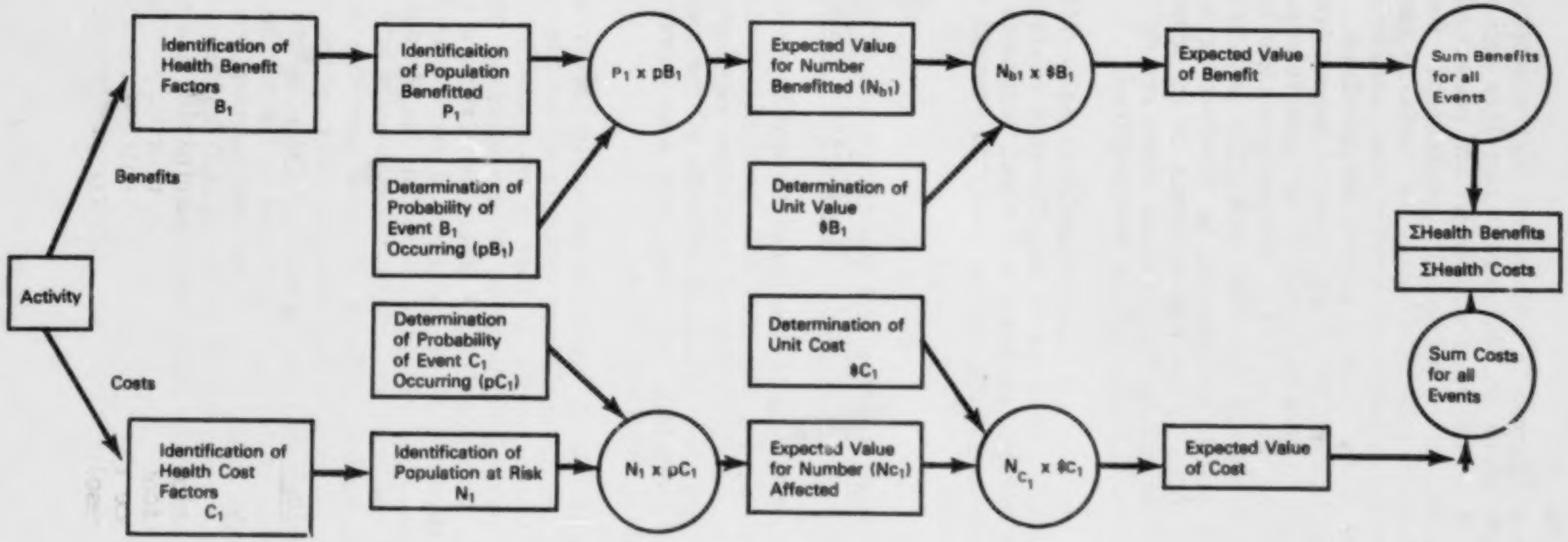
Finally, we explore and make as explicit as possible the moral and ethical considerations involved in benefit-cost analysis of this type. This is in no sense an attempt to formulate moral judgments but is, rather, an attempt to show at what steps in the analytic process ethical and moral values are implicit.

C. Process of Identification and Quantification of Positive and Negative Factors Associated with Health Benefit-Cost Analysis

In an effort to evaluate the benefits and costs of radiation regulation, it is important to obtain the best data possible on the physical and biological factors, i.e., distribution of radiation exposure and dose in the exposed population and the biological effects of the radiation, before the effort is made to transform such data into some common unit of account, say, a value expressed in monetary units.

The process of health benefit-cost analysis for any of the various activities resulting in radiation exposure of people or alternative activities to the same ends which result in less or no radiation exposure (see Figure III.1) involves: a) identification of the agent(s) or factor(s) affecting health in a positive (beneficial) direction and in a negative (deleterious) direction; b) determination of the spatial and temporal distribution of these positive and negative agents or factors in the population; c) determination or estimation of the probabilities and/or degrees and incidence of beneficial effect and of deleterious effects of these positive and negative agents or factors in the study population samples yielding the data; d) calculation of the beneficial or deleterious impacts of these agents or factors on the total population expected to be exposed on the basis of the determined or estimated incidence values in study populations and assumptions concerning dose-response relationships; and e) transformation of health impact values into common units of account for comparison of health benefits and health detriments (costs), e.g., dollars.

Figure III.1


Activity
Benefits
Costs
Identification of Health Benefit Factors B_1
Identificaition of Population Benefitted P_1
Determination of Probability of Event B_1 Occurring (pB_1)
P_1 x pB_1
Expected Value for Number Benefitted (N_{b1})
Determination of Unit Value $\$B_1$
N_{b1} x $\$B_1$
Expected Value of Benefit
Sum Benefits for all Events
ΣHealth Benefits
ΣHealth Costs
Identification of Health Cost Factors C_1
Identification of Population at Risk N_1
Determination of Probability of Event C_1 Occurring (pC_1)
N_1 x pC_1
Expected Value for Number (Nc_1) Affected
Determination of Unit Cost $\$C_1$
N_{C_1} x $\$C_1$
Expected Value of Cost
Sum Costs for all Events

One property of ionizing radiation is that it is differentially absorbed by various tissues of the body. This property is the basis of diagnostic radiology. Another property of radiation, that it can cause reproductive sterilization or destruction of cells, is exploited in radiotherapy. Although these medical uses of radiation have positive effects (benefits) on health, there may also be some undesired side effects that are negative or deleterious. Accordingly, it is necessary to detail both positive and negative effects, their impact and their transformation into some common unit of account, if possible. The radiation that is produced in nuclear power production is a natural consequence of nuclear transformations. Where a population is irradiated coincidentally with achieving another purpose, as in the generation of nuclear power, only the negative effects of the radiation need be evaluated.

Radiation protection may imply the substitution of a non-radiation for a radiation related technology in some cases; for example, the substitution of fossil fuel for nuclear in generating electricity. But there are health and non-health related environmental effects not reflected in the market costs associated with the alternative which also must be evaluated in a corresponding, conceptually consistent, manner.

In Figure III.1 is given a schematic block diagram that represents the steps in the process of research and analysis associated with the evaluation of the health effects--benefits and costs--of alternative technologies or strategies involving different amounts of radiation exposure.

If the dollar costs of the resource or factor services used to carry on an activity represent the total social costs, it is not necessary to undertake extra-market benefit and cost analyses at each of the many stages at which the various factors supplying services to the activity are produced. On the other hand, if there are extra-market social costs, i.e., adverse health and environmental effects not somehow incorporated into the dollar costs of the services used in a given activity, it is then necessary to analyze the extra-market, or external, costs associated with each activity that feeds into the activity of primary concern. For example, it is known that the externalities associated with the generation of electrical energy, whether by combustion of fossil fuel or nuclear reaction, are not confined to the power plant. Accordingly, non-market compensated adverse effects associated with such activities as mining (whether coal or uranium), fuel processing, waste disposal, etc., require the analytic and research treatment implied by the schematic diagram in Figure III.1. Non-health related environmental effects may also be involved depending on the nature of the activity.

D. The Methodology of Health Benefit-Cost Evaluation for Ionizing Radiation

1. Summary

In this section is presented a deterministic analytical model employing production functions to illustrate the procedures which can be used in benefit-cost analysis once the conceptual difficulties associated with a given social goal have been resolved and when complete information is available. Discussed briefly are the ways in which the parameters--inputs and outputs--of the production function are estimated. For elements determined by an unconstrained market the estimation is straightforward. However, in certain important instances, the market price may be distorted, and thus require an adjustment if it is to be used as a measure of benefit. Alternate methods for estimating costs or benefits are treated briefly.

Other parameters are not ordinarily measured in monetary units. The problems of incommensurability and the ways in which parameters measured by different units can be reduced to a common unit are considered. It is indicated that these procedures always involve implicit or explicit value judgments. The concept of dominance is described as a technique for avoiding the necessity for reducing all terms to the same unit.

The problem of incomplete information is subdivided into two parts. When the range of uncertainty in the estimates is narrow the analytic procedures can still be used to good effect. However, it is argued that when the estimate of the probability of occurrence of a grave event is itself uncertain then a different mode of analysis is needed.

The final part of this section deals with social values affecting the benefit-cost analysis. Discussed are distributional affects, that is, the fact that the people who stand to gain from the introduction of a process may be different from the people who will bear the cost or health burden. Another factor discussed is the relation between uncertainty as to benefits and costs prior to the establishment of a new process and the cost of terminating the process if the actual experience shows the initial estimates were seriously in error. In the case of a nuclear power source with a high capital cost, the price of reversing the initial decisions may be so high that the decision is virtually irreversible. These ideas are brought together within the concept of risk avoidance. It is shown that if standard benefit-cost estimation practices are followed, the monetary equivalent of a health or social cost will invariably be undervalued.

2. Introduction

The International Commission on Radiological Protection (ICRP) has recommended (2) that the total benefits (B) from activities involving radiation must be demonstrated to be greater than total (private and social) costs (C), and that regulating, moderating, or controlling radiation doses must be carried to the point where the gain from dose reduction achieved no longer warrants the increment in costs of control. This, of course, is a simple representation of the standard criteria used in benefit-cost analysis, i.e., that $\Delta b/\Delta c - 1$ and that $B- C > 0$. It should be pointed out that procedurally, it is necessary to equate the incremental benefits and costs to determine the levels of radiation doses and costs of control that maximize the total net benefit--or minimize the total net cost--a condition that should be realized prior to the determination of whether or not the benefits from the radiation exceed the costs.

The ICRP has assumed that the conditions required to give normative significance to results of benefit-cost analysis hold in situations concerning biological effects of ionizing radiation. It is conceivable that either in general or special cases this assumption is unwarranted, and this matter will need to be examined in due course. For the moment, however, it may be instructive to determine what procedures should be followed in order to apply ICRP's summary criteria for determining the "as low as practicable" dose levels.

3. Consideration of Benefit-Cost Analysis for Achieving Lowest Practicable Levels of Ionizing Radiations

Many quantitative procedures have been devised to help decision-makers choose from among several courses of action. However in order to carry out a quantitative evaluation for a complex social undertaking, one must make a large number of assumptions, although some of them may be of dubious validity. The apparent objectivity of a numerical calculation tends to obscure the weaknesses in the reasoning upon which the computation may be based. For this reason it is preferable to regard benefit-cost analysis as part of the process of dissecting the intricacies of a problem rather than as the only tool for generating definitive answers.

We proceed in four steps. First, we consider a mathematical framework for benefit-cost analysis. We illustrate its use by considering processes in which ionizing radiation is an intrinsic, useful product (diagnostic radiology) and in which the radiation is an unwanted by-product (nuclear power generation). In particular, in Section 4, we proceed as though all the necessary information were freely available and entirely accurate. As an expositional device, we put aside the complications of reality. Once we show how the various costs and benefits fit together conceptually we turn to the difficulties in establishing the validity of the values of cost and benefit that are needed for the analysis.

In Section 5, we consider the problems of estimation and measurability. We discuss the ways in which costs and benefits can be estimated. We will consider in particular strategies to be followed when the available data are in different units of measure; money, life expectancy, quality of life, environmental change, etc. In Section 6, we discuss the complications in estimation that arise when the available information is incomplete or uncertain. In Sections 7 and 8, we return to the question of risk and the problems associated with the long-lived nature of some of the health and non-health environmental costs.

4. Structuring the Benefit-Cost Analysis of Ionizing Radiation

For a program involving radiation, e.g., an X-ray program for diagnostic purposes, benefit-cost analysis is useful in helping to formulate and answer two questions: 1) what is the best scale of the program? and 2) what is the best mix of inputs for the scale? To answer these two questions, it is necessary to perform two optimizations. A program to achieve the "lowest practicable level of radiation" in accordance with the two optimizations would provide the desired result in the following sense: it would indicate the point beyond which lowering of the radiation from this level, for example, by adding shielding, would entail more costs than benefits.

a. Costs: Inputs and Outputs

To fix ideas, consider a hospital planning a diagnostic X-ray program. It can buy an expensive machine which economizes on the technician's time if it decides on a large-scale program, or a less expensive machine if the program scale is to be smaller. It can buy a machine with more safety features, but only at a greater cost in the machine or in the technician's time. The output of the machine is measured in units corresponding, say, to the number of X-ray exposures for patients per month. The inputs to the program include the capital cost of the machine to be amortized over some period of time, electricity, and the technician's time. These are costs measured by markets and we can use interest payment, wage payments, prices of electricity, as measures of cost. (These costs are sometimes called internal or private). But there are other costs, just as real and not directly measured in monetary units. There is the cost entailed because the radiation dose required for the diagnostic procedure can induce a malignancy in the patient. There is also the undesired radiation to the patient. In the process of generating a desired X-ray of teeth, for example, the gums and other parts of the face are also irradiated. These latter doses are unwanted and represent costs that may be reduced by increasing the shielding or by other ways that may raise the cost of the X-ray procedure. Similarly, the technician may be irradiated, and this, too, represents a cost. (These latter costs are sometimes called external and represent elements of total social cost.)

We shall first assume that all the costs and benefits have been estimated correctly. One way to schematize these interrelationships is by a production function:

(1) $X_1 = f(Y_1, Y_2, Y_3, X_2, X_3)$

where X_1 is the output, number of desired X-ray exposures,

Y_1 is the capital input of the machine,

Y_2 is the technician's time,

Y_3 is the amount of electricity used,

X_2 is the unwanted X-ray dose to the patient, and

X_3 is the unwanted X-ray dose to the technician.

Often X_2 and X_3 are thought of as unwanted outputs; here they are treated as unwanted inputs, which may at first seem a little strange, but X_2 and X_3 are costs like the other inputs and it is convenient to treat X_2 and X_3 symmetrically with the other costs. The production function incorporates the idea of trade-off. For the same output X_1, we can decrease the technician's time (Y_2) at the price of a bigger capital input (Y_1); we can economize on the technician's time at the cost of exposing him to a little more unwanted dosage (X_3); we can cut down on X_2 with a more expensive machine (Y_1) which more precisely directs the X-ray beam.

Even though the X-ray exposure, X_1, is a necessary product, it is not desired for its own sake but as an intermediate product. Output X_1 is used in turn as an input for another production activity. (X_1 considered from the point of view of an output is a benefit, but X_1 considered from the point of view of an input is a cost.) In this second activity, the X-ray dosage, film, technician's time, and doctor's time are turned into diagnoses. Thus, we write down another production function, incorporating another round of trade-offs:

$$(2) \quad D = g(Z_1, Z_2, X_1)$$

where D is the output, the number of diagnoses,

Z_1 is the doctor's time in interpreting the X-ray,

Z_2 is the film, and

X_1 is the X-ray dosage.

(Other inputs of the productive activity are neglected for convenience.) As indicated earlier, more sensitive equipment can cut down the dosage per patient which enters into the estimation of X_1. There are obviously many other trade-offs but one example is enough for the idea.

We could go further and consider D also an intermediate product, again not valued for its own sake, but valued as an input in another productive activity which produces cures or increases life span. But for this illustration, we can stop here and consider D a final product. When it is viewed as a desired final product D is a benefit.

We can imagine that somehow, by direct market measured or by indirect estimates, the total benefits attributable to each number of diagnoses is calculated. We plot this information as curve B(D) in Figure III.2. On the horizontal axis, D measures the scale of the number of diagnoses.

We are now ready to illustrate how the two optimizations are performed. For any particular output level of diagnoses, for example D*, there are many possible input mixes which could produce that level. Suppose

$$\underset{\text{input mix 1}}{(Y_1^1, Y_2^1, Y_3^1, X_2^1, X_3^1, X_1^1, Z_1^1, Z_2^1)} \quad \text{and} \quad \underset{\text{input mix 2}}{(Y_1^2, Y_2^2, Y_3^2, X_2^2, X_3^2, X_1^2, Z_1^2, Z_2^2)}$$

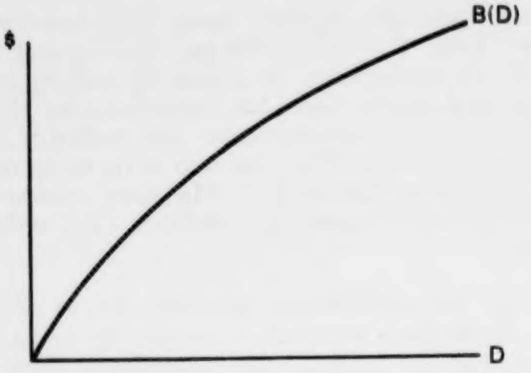


Figure III.2

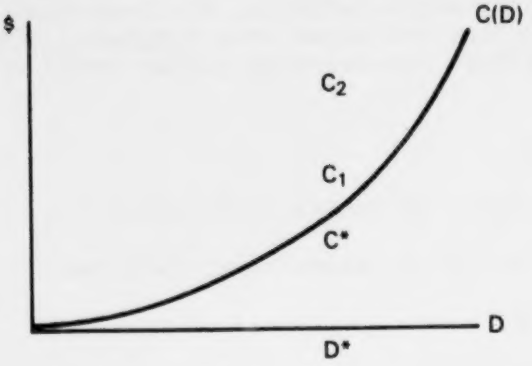


Figure III.3

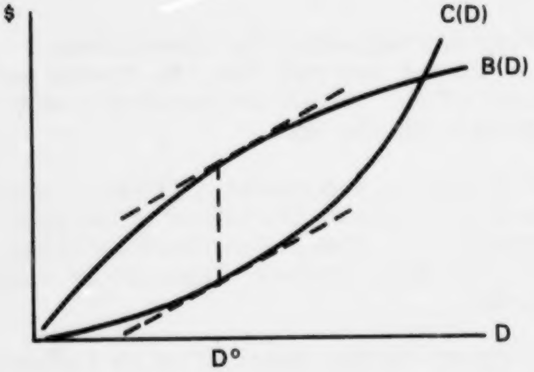


Figure III.4

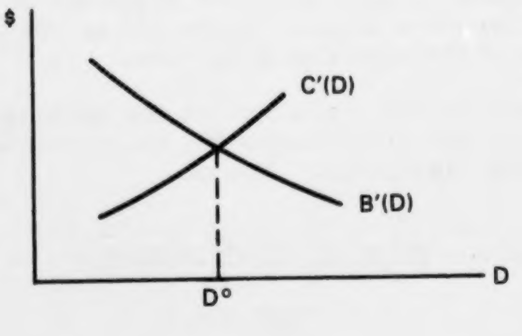


Figure III.5

are two such input mixes capable of achieving D*. For each input, we have an estimate of its unit cost, by direct market measurement or by indirect estimation. As a practical matter, the estimation of the health costs of X_1, of the costs of the unwanted radiation to the patient (X_2), and the costs of the unwanted radiation to the technician (X_3) is very difficult.

Setting aside for the moment this very difficult practical matter, we imagine that the cost of X_2 and X_3 are estimable for each level of X_2 and X_3 radiation exposures. The total cost of all the inputs can now be calculated for each input mix. Suppose for input mix 1, this total cost (including both internal and external costs) is C_1, and for input mix 2, it is C_2, and we plot these two costs associated with output level D* in Figure III.3. We can imagine calculating the total of all costs for all input mixes capable of achieving D*. There would be some lowest total cost and an input mix associated with it. (To be mathematically precise, there would be a greatest lower bound.) We plot this lowest cost C* on Figure III.3. In like manner for each possible output level, we find that input mix capable of achieving it with the lowest cost and plot that cost against the corresponding output level. The graph of such least cost points is C(D) in Figure III.3. The process of finding the least cost combination for each output level is the first optimization. This optimization specifies the best input mix for each possible output level. In this calculation, the external cost of unwanted radiation is included along with the cost of defensive measures and the least cost combination achieves the "lowest practicable level" of radiation for any given program size.[1]

The second optimization is much simpler, given B(D) and C(D). We plot B(D) and C(D) together on Figure III.4 and ask what is the best scale of program size? The answer is determined by the largest gap between the two curves; here the net benefits (the benefits B(D) minus the costs C(D)) are greatest. This is shown at D^o in Figure III.4. If we compute the marginal benefits B'(D) and marginal costs C'(D) in Figure III.5, D^o is also the point under which the marginal benefits are equal to the marginal costs ($B'(D)=dB(D)/dD$ and $C'(D)=dC(D)/dD$). At point D^o, an expansion of the program by one unit (arranging the inputs in the appropriate least cost way) leads to incremental (marginal) benefits just equal to incremental (marginal) costs. Thus at D^o, there is no gain by expansion by one unit. A similar argument

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[1] Just as in microeconomic theory with private factors of production, these least cost combinations have the following mathematical property: Suppose X_2^* and Y_1^* are part of the least cost mix of achieving D* number of diagnoses. Suppose, also, that τ is the marginal damage of radiation exposure to patients while r is the marginal rental cost of capital. Then

$$\frac{\partial f}{\partial Y_1} \Big/ \frac{\partial f}{\partial X_2} = r/\tau$$

The marginal trading off of a little more shielding for a little more capital cost is an important part of searching for the best defensive strategies.

goes for contraction by a unit. By the second optimization, the best scale for the program is where the net benefits are largest, or equivalently where the marginal benefits are equal to the marginal costs.[1] (Of course this second optimization rule should not be applied blindly. In Figure III.6, the biggest gap is at D^2 but the net benefits are negative and no program is better than D^2; at D^3 in Figure III.7, the marginal costs are equal to the marginal benefits but here the net benefits are being minimized.) To perform a proper benefit-cost analysis of an optimal program, both optimizations must be performed simultaneously. It is not sufficient to first pick the optimal program size and then choose the optimal level of safety.

b. Radiation as a Pollutant

In some processes radiation emission is a wholly undesired product; an unwanted "side effect." In such cases, we can use the same framework as before. Consider a nuclear power plant: its desired output is electricity and its conventional inputs are capital, labor, nuclear fuel, and so on. Besides these costs, there is also radioactive emission which we treat as we did above as an input or factor of production. Again there are tradeoffs in the inputs. For the same output level of electricity, we can decrease the radioactive emission by increasing the capital cost, with more shielding or by more carefully training the operating personnel. We write the production function

$$E = f(Y_1, Y_2, X)$$

where

E is the output, electricity,

Y_1 is the capital input, or factor of production,

Y_2 is the labor input, or factor of production, and

X is the radioactive emission, also an "input" or factor of production.

Setting aside the practical problems of benefit measurement, we can posit the existence of a benefit curve $B(E)$, just as in Figure III.2, but with E in place of D. For each level of output E, we find the least cost mix of inputs to achieve it.

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[1] Consider a mass screening program where the incidence of the disease for which the diagnostic radiology is undertaken is not uniformly distributed among all age cohorts. Reducing the scale of the program by eliminating progressively portions of the tail of the probability distribution would be one way in which to alter the scale of the program incrementally.

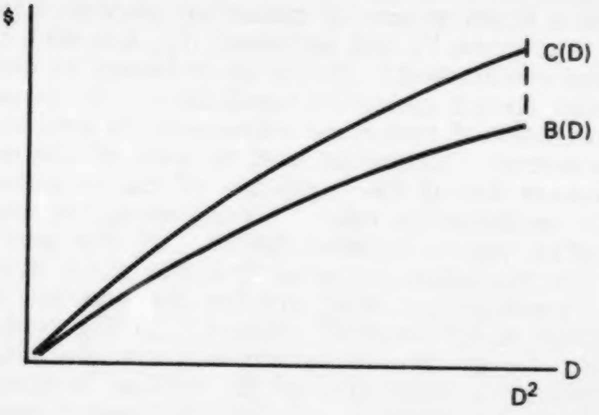


Figure III.6

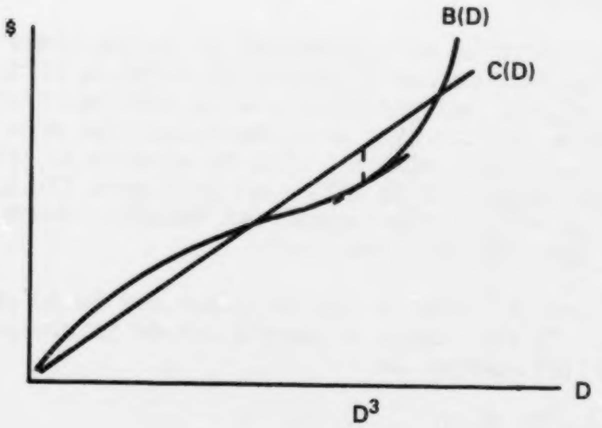


Figure III.7

There are great difficulties in achieving this. What is needed is the marginal damage of X. That is, for the levels of E, Y_1, Y_2, and X in question (and any other variables which might affect the marginal damage), we need to estimate the damage caused by increasing X by one unit. To make this estimate, we need to estimate its three underlying components: 1) The "source term." For a given amount of radiation generated in a particular plant with capital structure Y_1 and personnel Y_2, how much of this radiation is released into the environment? Radiation releases to the atmosphere are easy to measure under normal operation conditions. It is not possible, however, to measure releases of radiation subsequent to accidents which have not (or not yet) occurred. Estimates must be made of the probability of occurrences of releases and of the magnitude of the releases from accidents. These are difficult estimates to make. Furthermore, the magnitude of these probabilities is still subject to much debate. 2) The environmental transfer function. How is the radiation released from the plant dispersed throughout the environment? In particular, what are the incremental "doses" received by the population from an incremental release? 3) The health effect. For a given dose distributed over the population what are the health effects attributable to the incremental generation of X? (EPA's "Environmental Radiation Dose Commitment: An Application to the Nuclear Power Industry" (3) is an example of the methodology required.) The problem of estimating the marginal cost appears to be simpler for the X-ray machine than for the nuclear plant. For the X-ray machine, the environmental transfer function can be estimated with little difficulty.

Unfortunately, there is no alternative to facing these difficulties and dealing with them as best we can if we are to estimate efficient levels of radiation, safety effort, and program scale in economic terms. For the moment, we imagine that these difficulties are surmounted; for each level of output E, we have found the least cost mix of inputs to achieve it; the graph of these least cost amounts plotted against E is C(E), as in Figure III.3, but with E in place of D. And, as before, the largest net benefit, where B(E)-C(E) is maximized, is the best scale of the plant.

In practical applications, a nuclear plant may be in competition with a fossil fuel plant. In this case, we have a second production function to generate the same final output E:

$$E = g(Z_1, Z_2, S)$$

where

Z_1 is the capital input of the coal-fired station,

Z_2 is the labor input, and

S is stack emissions, another factor of production and "input."

Combining the two possible productive activities, we have the aggregate production function:

$$E = h(Y_1,Y_2,X,Z_1,Z_2,S), \text{ where h is defined by}$$

$$h = f(Y_1,Y_2,X) + g(Z_1,Z_2,S).$$

As before, for each E we choose that mix of (Y_1,Y_2,X,Z_1,Z_2,S) which minimizes the total cost (internal cost plus external cost, or social cost) of providing E. The plot of these least costs against E defines a new cost function C(E). Suppose for some E^* the least cost mix of achieving it is $(Y_1^*,Y_2^*,X^*,Z_1^*,Z_2^*,S^*)$. This input mix defines the best mix of input factors for each productive activity, fossil and nuclear, to achieve E^*. By substituting (Y_1^*,Y_2^*,X^*) into f and (Z_1^*,Z_2^*,S^*) into g, we also find the best scale of the nuclear effort balanced against the fossil effort, for that level of electricity production E^*.

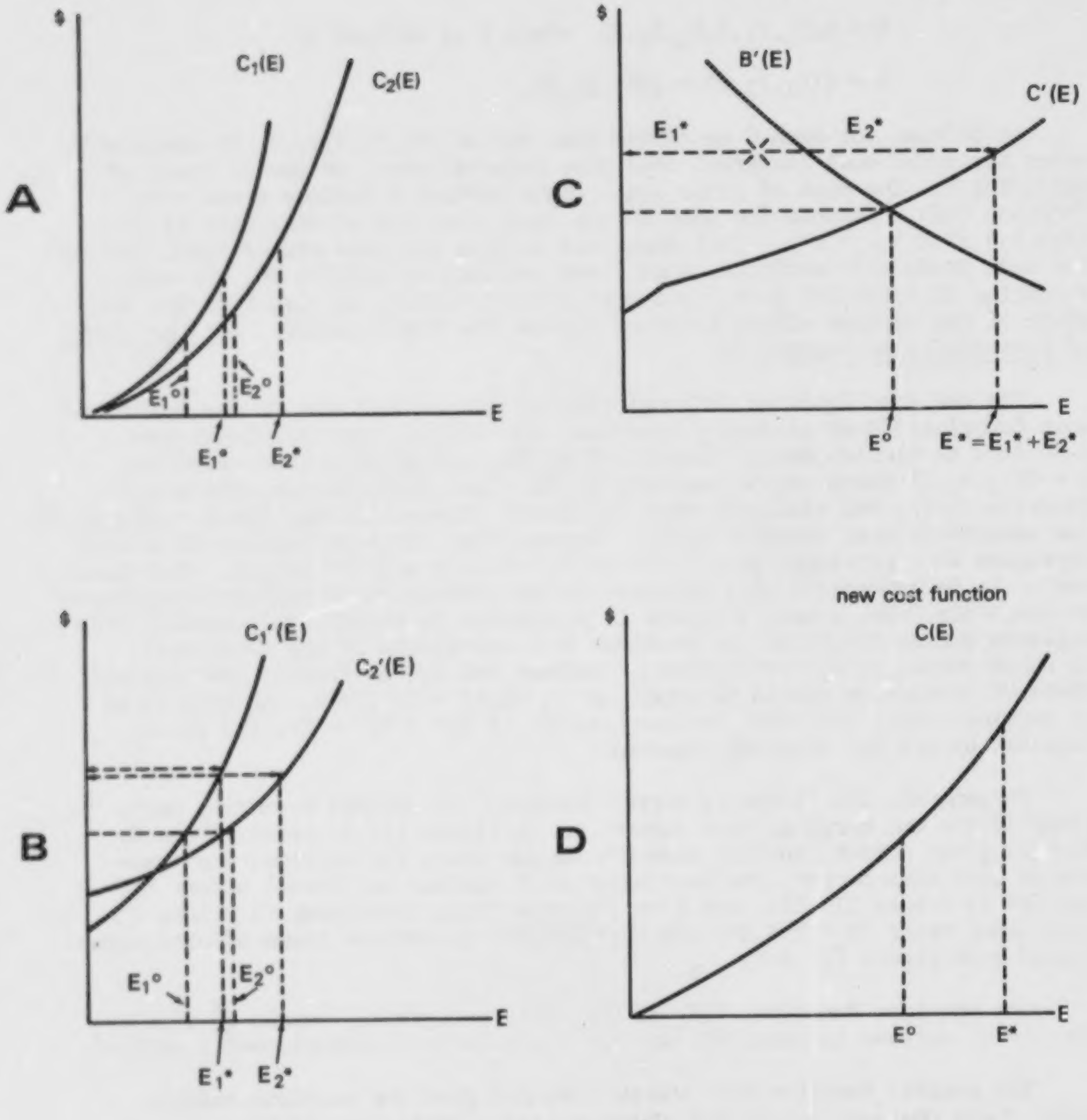
The new cost function C(E) can also be defined in terms of the individual cost functions (just as supply functions are derived from individual cost functions in microeconomic theory). From the nuclear production function $E = f(Y_1,Y_2,X)$ there can be derived, by the first optimization, the cost function $C_1(E)$; and similarly from the fossil production function $E = g(Z_1,Z_2,S)$ the associated cost function $C_2(E)$. Suppose that the best balance to achieve aggregate E^* electricity generation is E_1^* nuclear and E_2^* fossil. For these two to be in balance, a unit decrease in the production by nuclear should save in costs just what a unit increase in production by fossil would entail (this neglects corner solutions and problems with smoothness of the functions). In other words, at E_1^* production by nuclear and E_2^* by fossil, the marginal costs of production should be equal, or $C_1'(E_1^*) = C_2'(E_2^*)$. At this level of marginal cost, the total industry output is $E_1^* + E_2^* = E^*$, the amount supplied by the two programs together.

In general, the "industry supply function" is defined by adding horizontally the two marginal cost curves, as in Figure III.8, panels B and C. For any given output, in this case E^*, we can trace the marginal cost associated with this output, the best balance of nuclear and fossil effort (E_1^* and E_2^* in Figure III.8B), and from the underlying total cost functions the best input mixes (Y_1^*,Y_2^*,X^*) and (Z_1^*,Z_2^*,S^*) to achieve these efforts (associated with Figure III.8A).

The new cost function, C(E) of the above paragraphs, equals $\int_0^E C'(x)dx$, for the C' defined in panel 8C, so that the notation is consistently defined.

The benefit function B(E) has not changed from the previous example where there was just one method of generating electricity, nuclear. Again the optimum scale for electricity generation is defined by the biggest gap between the new cost curve and the old benefit curve, or where the old marginal benefit B'(E) and new marginal cost curves cross, at E^o in panel 8C. Optimal aggregate scale E^o of panel 8C also specifies optimal individual program efforts E_1^o and E_2^o of panel B, and from the least cost input mix

Figure III.8


A
$
C1(E)
C2(E)
E1°
E2°
E
E1*
E2*
C
$
B′(E)
C′(E)
E1*
E2*
E
E°
E* = E1* + E2*
B
$
C1′(E)
C2′(E)
E1°
E2°
E
E1*
E2*
D
new cost function
$
C(E)
E
E°
E*

associated with each point on the individual cost curves C_1 and C_2, we also have specified the optimal input mixes (Y_1^o, Y_2^o, X^o) for nuclear and (Z_1^o, Z_2^o, S^o) for fossil power production.

c. Subsuming the Intermediate Product

In the last example, there were no intermediate products. It is also possible to formulate the first example of the x-ray diagnosis program without an intermediate product. All that is needed is to substitute equation (1) into equation (2) to yield

$$D = g(Z_1, Z_2, f(Y_1, Y_2, Y_3, X_2, X_3)).$$

Now we have a single production function of diagnoses specified by inputs of capital to the x-ray machine, technician's time, unwanted dosage to the technician, unwanted dosage to the patient, the film, and the doctor's time. Minimization over these variables to define least cost combinations will lead to the same cost curve as C(D) in Figure III.3. If there is concern about the right amount of lead shielding for the patient, we do not need to talk explicitly about the intermediate product X_1, at all. In some applications, it is useful to aggregate intermediate production functions (eliminating intermediate products from explicit analysis) to use final product functions by themselves. In this way, it is shown that the two cases, the X-ray machine with its wanted radiation, and the nuclear power plant, with its unwanted radiation, can be treated by the same mathematical formalism.

5. Estimation and Measurability

The production function discussed in Section 4 above can contain many terms that represent a variety of costs and benefits. Some are measured in the market, that is, by their actual or expected cost in money or by the price which the user will pay for the product. Others are not directly measured in monetary units. For those measured in the market, we can take the current market price, wage scale, etc., as the basis for calculations. Costs and benefits which are not measured in the market but are measured in other currency, for example, years of life lost, must be estimated in other wavs. Further, in many analyses it will be essential to arrive at a conversion factor from each measure to a single common measure before the benefit-cost calculation can be made.

Let us consider the problem of a hospital planning a diagnostic radiology program. Inputs such as the capital cost of the X-ray equipment, film, electricity, technicians' and physicians' salaries, rent, amortization, etc. are measured by the market. We can use price lists, wage scales, interest rates, power rates, etc., to estimate these costs.

The value of the benefits may be estimated in the same way. The desired final product is the diagnosis. If there is an unconstrained medical market, we could take the market price--the fee for a diagnostic X-ray examiniation--to be the measure of this benefit. The major virtue of this estimate is that it is rather easy to make; otherwise, it has little to recommend it. The price of a diagnosis will vary over a wide range--free for some patients, partially subsidized for others. The price is subject to change by doctors as a subjective response to inflation or the effect of health insurance on the behavior of physician and patient. What is perhaps the most important complication is that almost all patients lack the information by which to calculate the worth of the diagnosis to them.

In such cases, economists might try to make their own estimates of the health benefits attributable to the diagnoses by--for example--calculating the expected increase in the total wages earned by the patient as a consequence of the cure and to the extent that the cure was attributable to the diagnosis. Since many patients and many different wage scales will be involved, some kind of average must be computed. But a simple average carries the implication that the same benefit in years of productive life saved is greater for the higher paid person than the lower, all other things being equal. Not all people concerned will agree upon this value system.

In like manner estimates need to be made of the years of life lost by exposure to unwanted radiation. Two estimation steps are needed. First, there is a cost computation in health units, for example. The expected value for the years of productive life lost is computed from the expected level of unwanted exposure. Second, a monetary value is placed on the lost time by estimating the expected present value of the lost wages. The complications of making plausible estimates of the likelihood of cancer or the decrement in length of life that can result from exposure has been treated in detail in the BEIR report (1). As with the dollar estimates of the benefits of diagnostic radiology, the costs of exposure may be estimated from the expected present value of the lost wages from the increased probability of morbidity and mortality. It is worth noting that the present value may be a very unreliable estimator because the overt onset of cancer will, in many instances, be a decade or more after the time of exposure.

Another problem in estimation has to do with the variation in physician performance. Since the end benefit is increased years of life or decreased morbidity, this variable needs to be evaluated.

Similar difficulties arise in estimating the benefits accruing to power generation. The value of the benefits of electricity generation can in principle be measured by consumers' willingness to pay for it. But while there are markets for electricity and market prices for it, care must be taken in using these prices as the measure of benefit. Electric utilities are franchised monopolies and prices are regulated. Before using electricity prices as a measure of benefit, we may want to make adjustments in our calculations that take into account the ways in which price is distorted from being an appropriate indicator of benefit value.

Let us consider further the strategies that might be employed when benefits and costs are of different kinds; e.g., money, years of life, quality of life, etc., are measured in different units.

Recognizing that it is difficult to derive unassailable procedures for putting the various costs and benefits in the same dimensions, for example, dollars, we suggest that it is useful to see how far it is possible to go without facing this problem. Wherever possible, we propose to subdivide the problem so that dollars can be compared with dollars and man-years, say, with man-years. In an analogous manner, it would be possible to consider the costs and benefits of different populations separately, deferring as long as possible the need to average the consequences over the disparate populations.

a. Processes of Power Production

When alternative technologies for processes in this category are compared, the benefits are directly commensurate so that one can compare alternative costs against a common denominator, such as megawatt hours. The costs will be of different kinds: market costs for producing equivalent amounts of power, environmental degradation costs, social dislocation costs, health costs, and the like. As indicated above, the costs imposed on different populations will need to be considered; costs to the plant workers, miners, people residing near the plant, those living at a greater distance from it, etc.

The strategy proposed here may be illustrated by a simpler process (which can be regarded as a sub-problem in the analysis of nuclear power); namely, the transport of nuclear materials. Only the mode of transportation (that is, by air, ship, motor vehicle, rail) is to be considered. The benefit is the same in each instance. It is implicit that we are considering the transport of the same type of radioactive material and hence that the kind of health risk will be the same. Therefore, in considering health costs, only the alternative quantitative measures of risk from exposure need to be evaluated. The probability of accident (or sabotage) will vary among the modes, as will the population exposed to accidental release of radiation as well as the expected severity of exposure. As long as expected exposure is greater for one mode than another, its associated health costs must be greater.

In some comparisons, the health and market costs need not be put in the same units. Suppose that, when benefits are equated, the health costs for one mode (X) were lower than for another, Y, and that the market costs were also lower for mode X than for mode Y. Then mode X dominates Y. Mode X is unambiguously less costly than Y no matter what dollar value is put on the health costs.

We can formalize this as follows:

Let benefits from either mode be B
Label the different kinds of costs; money, health, social, etc.
C_a, C_b, C_c....and hence we label the cost of mode X
C_{ax}, C_{bx}, C_{cx}....
We are interested in comparing $B - (C_{ax} + C_{bx} + \ldots.)$ with
$B - (C_{ay} + C_{by} + \ldots.)$.

The common decision rule is: choose X if
$[B - (C_{ax} + C_{bx} + \ldots.)] > [B - (C_{ay} + C_{by} + \ldots.)]$
and since the benefits are the same, we can rewrite the decision rule as follows:
Choose X if $\sum_j C_{jy} > \sum_j C_{jx}$.
But if $C_{jy} \geq C_{jx}$ for every j, that is, for each different kind of cost--then X dominates Y and the sums of cost need not be computed in order to apply the decision rule.

Let us explore this strategy further. For any specific adverse effect, say the occurrence of death, there is an *a priori* distribution that assigns a probability of death to each individual in the population at risk. Each mode may entail as a consequence an increase in this probability for some or all the members of the population. Call the increase in probability for a particular individual if mode X is used ΔP_{jx}. In order to compute dollar cost, we must associate with the increase in probability a *valuation function*

$$C_{jx} = v_j\ (\Delta P_{jx})$$

The values v_j will not be the same for all people unless, of course, insistence on equal value is the first principle of the social theory governing the assignment of value to a health factor. Thus, $C_x = \Sigma\ v_j(\Delta P_{jx})$ where C_x is the total health cost of alternative X. However, as before, we may be able to use the device of dominance to choose between alternatives X and Y. If $C_{jy} \geq C_{jx}$ for every j then $C_y \geq C_x$ no matter what the values v_j are (as long as they are finite), and we can use our decision rule to identify X as the preferred alternative. In the foregoing example, the choice between alternatives is based only on the probabilities of adverse events and not on the explicit health costs.

b. Diagnostic Radiology

There are several ways in which the statement of diagnostic radiology problems may be simplified. First, the radiological procedures are appropriately and readily separable according to the diagnostic problems they are intended to resolve. In this category, we can in principle estimate both the health and some of the other extra-economic costs, and the benefits in terms of increment or decrement in the probability of death. Since these parameters are in the same units, their ratios are dimensionless. In the analysis of at least some diagnostic procedures, the health benefits are so substantial that one need not consider the financial costs at all. They would be negligible when a year of life is assigned any reasonable monetary value.

Among the subproblems of diagnostic radiology, there are a number which can be treated in much the same manner as the problem of nuclear versus fossil fuel energy; that is, alternative diagnostic procedures can be compared. An example would be echocardiography versus radiography for the detection of morphologic cardiac abnormalities. If it can be determined that each procedure offers equivalent benefits in terms of diagnostic accuracy then they can be compared purely on the basis of costs. In the case of radiography, the costs contain both a monetary and a health cost, whereas it is currently presumed that echocardiography entails no health cost. And if the monetary cost of echocardiography is equal or less than radiography then the decision is obvious and the only remaining problem is to devise the process whereby radiology departments acquire the necessary ultrasound equipment and the expertise to use it.

Unfortunately, the above argument is predicated on the assumption that the benefits from the alternatives are equivalent. The assumptions need to be validated. Benefits can be defined in terms such as the reduction in the probability of death. But what if the correct diagnosis, D, will not improve longevity? It seems reasonable to assume that a positive diagnosis will benefit the patient and others in the reduction of pain as well as with respect to the poorly defined but real effects on the quality of life. The problem of putting such benefits together with increase in life expectancy is not easy, but may not always be avoidable.

The paradigm for economic theory would be to value these benefits by seeking answers to questions such as "What would you be willing to pay for a decrease in your pain but no increase in life expectancy?" Or, since virtually all information has value, "What would it be worth to dissipate your uncertainty and to know that you have an incurable cancer?" One may conjecture that if a benefit-cost analysis requires this level of benefit to be factored in, it is probably the wrong problem to study with this kind of analysis. It is more appropriately the problem for an ethical philosopher.

In most circumstances, a correct diagnosis at a given time will improve the prognosis. In this case, the comparison of benefits associated with alternative diagnostic procedures may be assumed to involve only the diagnosis and not necessarily treatment if it is assumed that the therapy will be identical whichever procedure is used for diagnosis. The effect of early diagnosis on the selection of therapeutic management is a subproblem of this model.

The usual way to represent benefits is by equations for each procedure of the following form:

$$\bar{b}_{D,x} = w_1 \, P_x(D,d) + w_2 \, P_x \, (\bar{D},d) + w_3 \, P_x(D,\bar{d}) + w_4 \, P_x(\bar{D},\bar{d})$$

where $P_x(D,d)$ is the probability of correct positive diagnosis

$P_x(\bar{D},\bar{d})$ is the probability of correct negative diagnosis

$P_x(D,\bar{d})$ is the probability of incorrect positive diagnosis

$P_x(\bar{D},d)$ is the probability of incorrect negative diagnosis

These probabilities are estimated for diagnostic procedure X. The w_i are weights or values that accrue for each possible outcome. One would expect that an error in diagnosis is of negative value and therefore that w_2 and w_3 would be negative.

We can write a similar equation for procedure Y

$$\bar{b}_{D,y} = w_1 P_y(D,d) + w_2 P_y(\bar{D},d) + w_3 P_y(D,\bar{d}) + w_4 P_y(\bar{D},\bar{d})$$

The decision rule would be choose X if $\bar{b}_{D,x} \geq \bar{b}_{D,y}$; otherwise choose Y. Clearly if X is better on purely diagnostic criteria, that is if

$$P_x(D,d) > P_y(D,d), P_x(\bar{D},\bar{d}) > P_y(\bar{D},\bar{d}), P_x(\bar{D},d) < P_y(\bar{D},d), P_x(D,\bar{d}) < P_y(D,\bar{d})$$

then the values or weights need not be assigned. X must be the better procedure in terms of benefit to the patient as well as diagnostic accuracy.

c. Therapeutic Radiology

While the theoretical tools for formal decision-making assessments in therapeutic radiology are the same as for those for diagnostic radiology, relevant importance of the various costs and benefit terms will be quite different. For example, the treatment is more costly, the radiation dose is much larger, and a much higher proportion of patients will be gravely ill.

To be sure, the health benefits and the health costs can be measured in the same dimensions, but this may be deceptive. In current practice radiation therapy for cancer is used only after the diagnosis of malignancy is certain. This will be true whether radiation is the only therapy of choice or whether it is used following surgery in order to decrease the likelihood of recurrence of the disease process. The probability of adverse effect of the radiation may be much larger than with the levels of radiation used in diagnostic radiology. Most adverse effects of the radiation will not be manifest until years after the exposure. An individual faced with imminent death from cancer may place a much greater value on a relatively short prolongation of life by radiation than on the avoidance of the potential future health effects of the radiation therapy.

Thus, for therapeutic radiology where changes in probabilities of adverse effects, ΔP_j and v_j, can vary so widely, separate calculations will need to be made for sub-groups of the population depending on age, sex, disease type, etc. Potential genetic effects introduce the time dimensions in a more insistent way. This issue and others of relevance to the foregoing discussion, i.e., treatment of uncertainty and irreversibility and measurement of the value of life or change in the probability of survival, are discussed at some length in the next two sections.

6. Complications Due to Uncertainties

Theory can be relatively simple and straightforward. But when actual policy decisions have to be made, it will not be possible to neglect some considerations which enormously complicate the problem of choice. In this section, we consider complications that arise from varying degrees of uncertainty. For the purposes of exposition, we discuss two degrees of uncertainty, "incremental" uncertainties and "major" uncertainties. In reality, the uncertainties of the problem vary from the almost certain to the nearly inestimable.

a. Incremental Uncertainties

In actual applications, we do not, of course, have the benefit and cost curves, nor the input costs associated with each input mix, nor even the production functions. Much has been written on the problem of decision-making without full information, and little will be said here except for a few commonsense remarks.

The programs we have been discussing by way of illustration are already in existence. We have both fossil fuel and nuclear power plants producing electricity. We are not at zero levels. We are already at some point like D^4 in Figure III.10. We do not need to know the whole B(D) and C(D), but we can content ourselves with incremental questions: should the program be expanded or contracted and should the mix of inputs be adjusted in some direction? (Again these questions should be handled simultaneously.) In particular, we need to seek an appropriate balance between unwanted radiation exposure and defensive expenditures limiting it.

It is generally true that we know most about the case we are currently experiencing, a fair amount about conditions slightly different from this status quo, and less and less about conditions more and more different from the status quo. The situation might be like that illustrated in Figures III.9 and III.10. There we have estimates of the costs and benefits and a spreading band of ignorance as we move away from the present case D^4. At D^4, where our knowledge is best, it appears that the total benefits are greater than the total costs (Figure III.9) so that the program at D^4 is better than no program at all. By the corresponding marginal curves in Figure III.10, it appears that marginal benefits are greater than marginal costs, so that some expansion of the program is in order. Just how much is very uncertain. It might be as little as to D^5, or as much as D^6. While it would be preferable to have more knowledge in any direction, it seems clear from the sketchy situation portrayed in Figure III.10 that knowledge about marginal costs and benefits for larger programs would be more useful than knowledge about marginal costs and benefits for smaller programs. Thus, the analysis provides ways to proceed without complete knowledge; some types of knowledge are more worth acquiring than other types (or directions), and from our understanding of the extent of our ignorance, we can sometimes specify the knowledge it would be most useful to acquire.

The same remarks can be made about the input mix. One changes the input mix in a particular direction as long as the marginal costs of doing so are smaller than the marginal benefits (in the final product attributable to the change). Because there are many uncertainties about the effects of input mix changes and the costs of input mix changes, the error band around the cost curves is drawn larger than the error band around the benefit curves.

Figure III.9

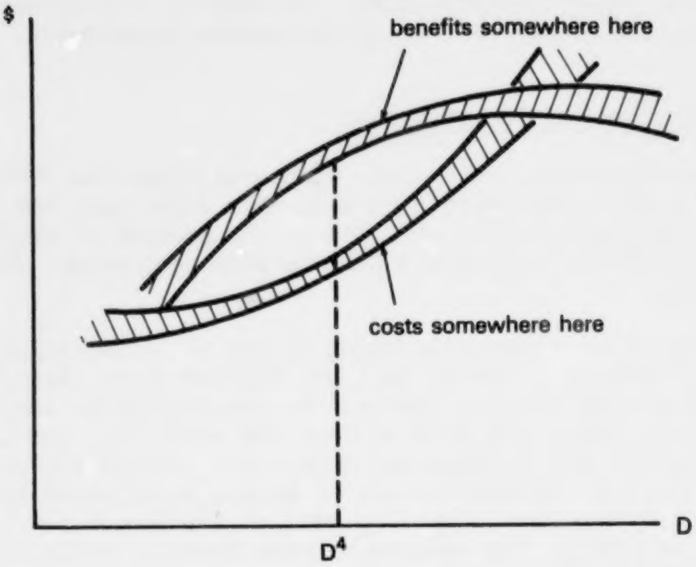
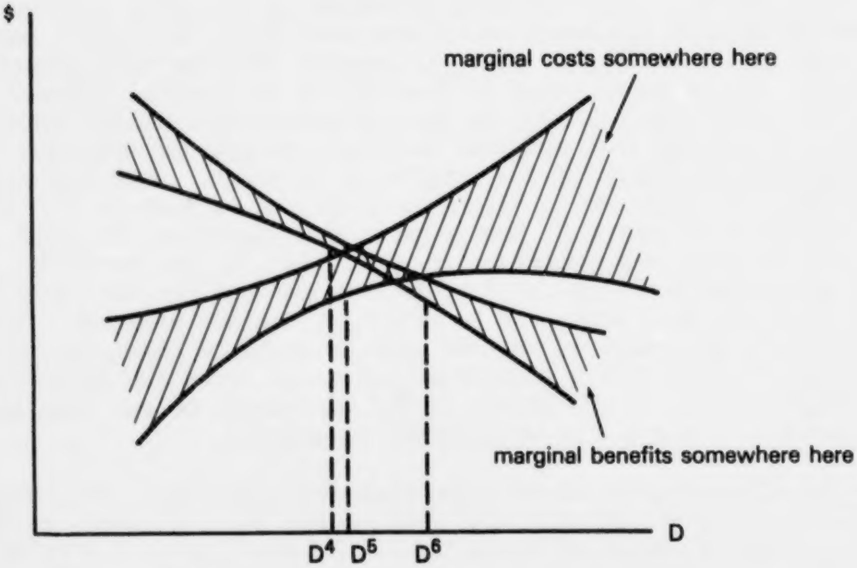


Figure III.10



b. Major Uncertainties

Virtually all the benefits and costs contain probabilistic components. Further, they vary with time in ways that are not completely predictable. The analyst when faced with a parameter which can fluctuate wildly will attempt to describe its behavior as a stochastic process. It is not our intention to enter into the intricacies of probability theory. However, the issue of accidents in nuclear power plants which has been a subject of extensive debate can be considered briefly as illustrative of some of the difficulties in estimating the consequences of some new activity.

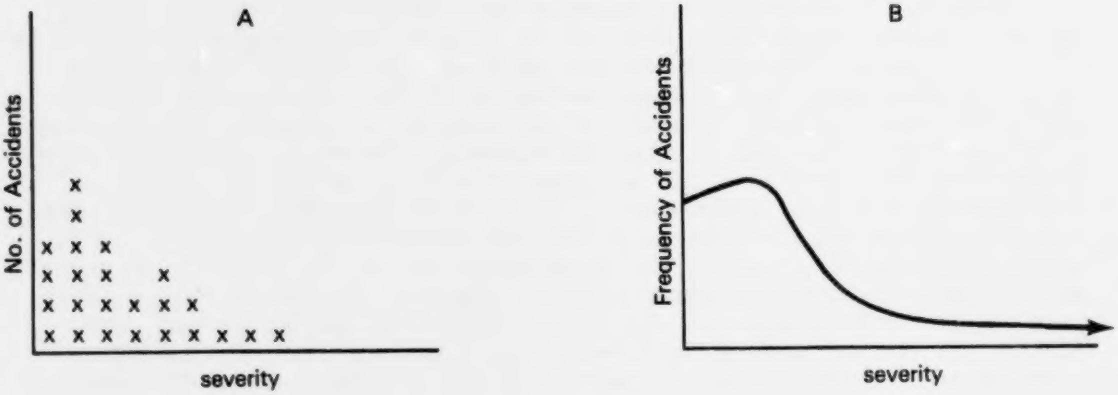
There are basically two strategies applied to this problem. First, physical theory is applied. Much of the physics of nuclear power plants is well understood. Information is available on such factors as radiation damage to materials, heat stress, mechanism of failure of welds, absorptivity of shielding, etc. Models of the behavior of plants, that is, simulated behavior, have been studied extensively. The model maker will attempt to make his mathematical model as close to reality as he can. Still, it is only a model. If the analyst has left out some important factor his model may well behave quite differently from the behavior of the process it is modeling. One way to verify the appropriateness of the model is to compare its performance with real power plants. However, in some instances, for example, the most drastic of the protective mechanisms in nuclear power plants, the actual test of performance would be prohibitively expensive since it would shut down and damage irreparably elements of a functioning plant.

Thus, the second strategy is to study experience. There are a number of power plants in operation, accidents have occurred and their severity has been ascertained. On the basis of experience to date analysts will frequently plot accidents in terms of their severity (see histogram in Figure III.11A).

From this plot (histogram), they will attempt to determine the underlying distribution (Figure III.11B), i.e., they will try to estimate the probability assignable to an accident of arbitrary severity. But because experience has been quite limited, the available data are sparse. As a consequence probabilistic estimates of events of catastrophic proportions will be highly unreliable. In this circumstance, analysts will ordinarily form a conservative (pessimistic) estimate, but the choice of a level of conservatism is a matter of judgment rather than computation. It is for this reason that some analysts have chosen to make a worst case analysis, that is, to assume that the worse conceivable accident will occur sometime. While this may make the cost side of the equation quite high it will still be finite. For example, such an argument has been used to suggest that nuclear power plants be sited as far as possible from centers of population. This will surely minimize the expected increase in morbidity and mortality, but will entail substantially increased costs for construction, power distribution, etc. Here, as before, a value judgment must be made.

However, conservative estimates alone should not be given to those who will be entrusted with arriving at a final decision. Rather, the role of the analyst should be to provide the decision-makers with an explicit and objective

Figure III.11



description of the benefits and costs involved including the valuation schemata on which they are based. Then if they so desire, the decision-makers may make conservative decisions, but at least their decisions will reflect their attitudes toward risk and not the attitudes of the analyst. In this manner, the role of the analyst becomes one of presenting the uncertainties involved as clearly as possible.

If the range of uncertain outcomes is limited, then an "incremental analysis" of the kind presented earlier in this chapter will be appropriate. Such will be the case where there is virtually no possibility of catastrophic events--for example, where we are concerned with small changes in levels of radiation leakage in diagnostic radiology as costed against more expensive equipment and shielding.

However, this form of incremental analysis is not appropriate when we consider the consequences of nuclear power plant accidents or the risk of sabotage from diverted fissionable materials. In these cases, we are faced with the consideration of very grave events occurring with very small and uncertain probability. The seriousness of these events is not easily measurable, as they involve attributes with different units, e.g., years of life, quality of life, effect on future generations, etc. The probability that any given scenario of events will occur is likewise difficult to estimate. Complicating both the measurability problems and the probability estimation problems is the additional consideration of inter-temporal effects on later generations. These inter-temporal effects may be irreversible. A discussion of the problem of irreversibility and its effect on future options will be given in more detail in the next sections.

Even if the consequences of any grave event could be measured in some common terms, and if its probability of occurrence in any given time period could be estimated, one must eventually address the question of how to reconcile events of very serious consequence and very small probability (e.g., nuclear power plant accident) with events of marginal consequence which can be more easily predicted (e.g., the steady state emission levels from those plants). A strategy for producing a given level of energy output must include expenditure allocations for both marginally reducing small levels of radioactive emissions and reducing the small probability that large numbers of persons will be accidentally and fatally irradiated. Such tradeoffs involving significant levels of risk can perhaps only be made at the final stage of the decision process. The analyst should insure that the relevant assessments of consequences and their probabilities filter through to the decision-makers in as explicit yet compact form as possible. The techniques found in the area of statistical decision theory should be helpful in compacting these many-dimensioned assessments.

7. Radiation Protection as a Factor in the Benefit-Cost Analysis

Benefit-cost analysis for alternate strategies for energy development or for other applications of radiation must include the immediate and long-term costs of regulation and compliance, as well as the research costs underlying the development of standards and protection guides.

The immediate costs involve such areas as staffing regulatory programs, monitoring sources of man-made releases of pollutants with attendant instrumentation development costs. A technical staff is needed to analyze existing scientific data and devise programs to develop new scientific bases for regulatory programs and standards development.

The development of standards and regulations is more advanced for radiation than for most other environmental contaminants. There are, however, jurisdictional problems in the regulatory application of radiation standards which can seriously affect the degree to which the public is protected against radiation hazards. (This is discussed at length in Chapter IV.) These same jurisdictional problems are now surfacing in the area of regulation of other environmental pollutants.

It may be desirable to visualize the future and long-term costs associated with: 1) the training of protection personnel; 2) educating operators and users of energy sources in sound personnel protection practices; 3) animal research directed towards investigating dose-response relationships for genetic and somatic effects of various types of pollutants as a basis for the rational setting of standards; 4) epidemiological studies of persons exposed to varying levels and kinds of pollutants; and 5) research in the development of improved protection methodology and procedures.

Another element of costs underlying various energy development strategies that is not often explicitly examined nor generally equivalent for all options is the cost of research and development assumed by all levels of government. When these costs are not distributed to the users, a subsidy exists for that process which must be taken into account in the benefit-cost analyses.

8. Risk Avoidance, Irreversibility, and the Distribution of Costs

There are two questions concerning the use of benefit cost analysis in decisions on activities involving the discharge of radiation to the environment that merit special attention. First, are the conditions for use of the analysis indicated by theoretical welfare economics likely to be satisfied? Second, assuming theoretical objections do not preclude some sort of analysis, how are the gains and losses in this special case involving human life, to be evaluated?

With respect to the first question, a major objection to benefit-cost analysis has been that it does not account for distributional effects. That is, as Samuelson (4) and others have argued, the fact that the gains to some individuals from a project outweigh the losses to others, does not in itself guarantee that the project will result in an improvement in social welfare, since society may for some reason be particularly concerned about the welfare of the losers. Of course, where compensation is made, most economists would agree that a project showing net benefits is socially desirable, and that the benefit-cost analysis carries implications for public decision. Where compensation is not made, it is probably fair to say that these same economists would recommend that planners give some attention to the distribution of gains and costs. For example, if it can be shown that most of those affected, favorably or unfavorably, will come from the same income classes, we are likely to be a good deal more comfortable with the implications of the analysis. On the other hand, it is possible to argue as Hicks did (5) that undertaking projects yielding an excess of benefits over costs regardless of distribution is likely to benefit virtually everyone in the long run, the idea being that if individual A is a net loser in project I, today, he may be a gainer in project II, tomorrow, and so on. This idea of a probabilistic compensation criterion has recently been more formally developed by Polinsky (6). If valid, it suggests that economists and planners need not worry too much about the distributional effects of a particular project, and concentrate instead on the more straightforward task of simply assessing the benefits and costs.

Without attempting to resolve here the difficult and challenging questions that have been raised with respect to the treatment of distribution, we wish to note that they apply with particular force in the study of processes involving radiation exposure. Some of the biological effects of radiation will be distributed indefinitely into the future, affecting increasing numbers in future generations. Ordinarily, future costs and benefits of a project are weighted by an exponentially declining discount factor. This is justified on various grounds, such as individual preferences for consumption now, rather than later, and the opportunity cost of capital employed in the project. The consequence in this case is that much of the damage to health entailed by operation in the near future of a system of nuclear power plants, occurring as it will in the relatively distant future, will have its economic cost washed away by discounting. At normal rates of discount of from five to ten percent, not many years are required for this effect to take hold. A human life lost in 1985 because of exposure in 1975 when discounted at 7% is worth, at present, only half as much as a life lost now. Accordingly, the question we face is, can the time stream of benefits, and perhaps more importantly, of costs, be evaluated by means of standard discounting procedures? Or ought we to give special consideration to the very unusual time distributions? The question is even more difficult than that faced in the intra-temporal case, i.e., in attempting to deal with the effects of a project on the distribution of welfare within a single time period or generation. The reason is that many, if not most, of those affected by the decision in the former case, for example on whether to go with the breeder reactor, will not have participated in the decision. How are their interests to be represented, if at all? Is it fair for the present generation to impose the associated radiation load on future generations? We certainly do not have definitive answers to these questions, but they are important, and for this reason, we feel they ought to be raised, at least (7).

Aside from the problem of distribution across generations of welfare, or its opposite burdens, that is raised by the very long-lived, virtually irreversible effects of a nuclear power program, there are some implications for the efficiency of investment in such a program. In particular, it has been shown that efficiency in the presence of irreversibility requires a more subtle balancing of benefits and costs than is envisioned in conventional benefit-cost analysis. A program or project having adverse effects that are for all practical purposes impossible to reverse should be developed on a smaller scale than appears warranted by a comparison of current benefits and costs--if it is anticipated that the burden of the adverse effects may grow more onerous in the future (8).

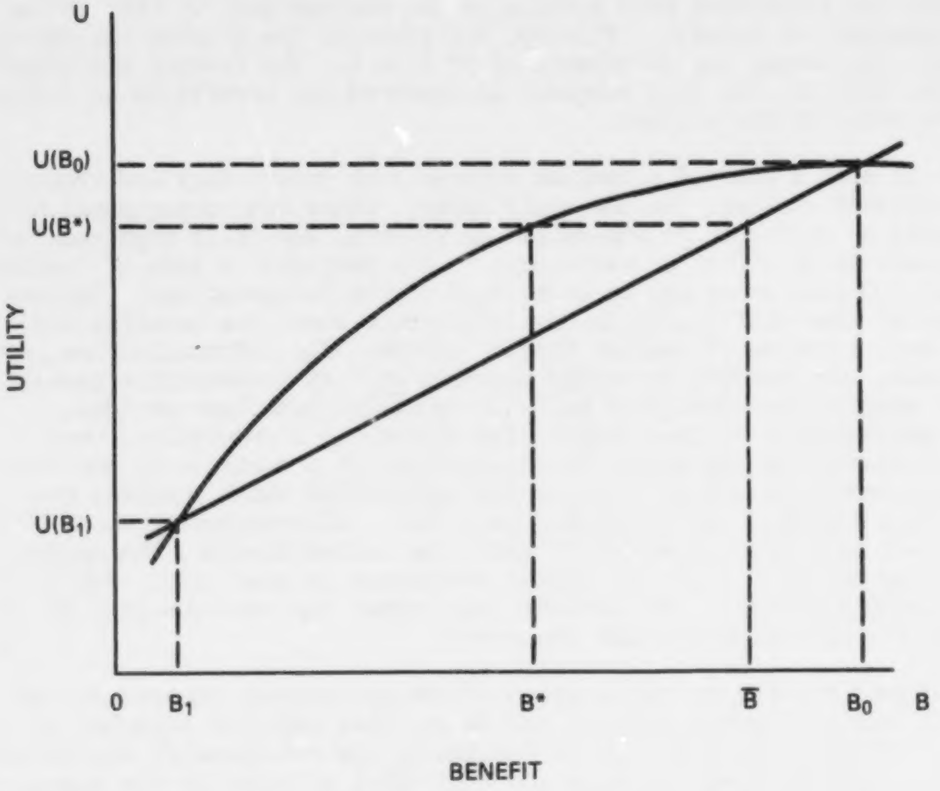
The sacrifice of current gains is a consequence of the restriction on reversibility. It appears that the conditions required for this result to apply may be fulfilled by investment in nuclear fission reactors, among other things.

A second important area to be explored with reference to an appropriate benefit-cost framework for analysis of radiation hazards is the treatment of uncertainty and the interaction between uncertainty and irreversibility. Although we know that the effects of radiation are not certain, all of the distributional considerations discussed above would remain relevant even if they were. We now wish to consider how uncertainty about the benefits and costs of a project involving the release of radiation ought to affect the calculations. The simplest way to factor in uncertainty, say about project costs, is to compute the expected value of the costs. For example, suppose it is known that the cost of a damaging event in the nuclear fuel cycle would be $100 million, and that its probability of occurring is .01, then the expected cost is $1 million. Although this simple calculation may be the best that can be made with the available data, it should be pointed out that it implies a rather strong assumption: that (social) utility is a linear function of income, or equivalently, that society is not averse to the risk associated with the damaging event.

It is ordinarily assumed, on the basis of much evidence, that in their economic behavior individuals are averse to risk. Yet, as Samuelson (9) and Arrow and Lind (10) have argued, it does not necessarily follow that a social choice should be characterized by risk aversion. Instead, because it is possible to spread the risk from a project among the large number of people who benefit, it has been suggested that the appropriate social decision criterion is simply the project's expected value. However, this risk-spreading argument does not seem to apply to radiation from a nuclear plant (11), since the amount of the radiation to each individual is not reduced even as the number of affected individuals is increased.

Let us consider briefly the implications of the proposition that individual attitudes toward the risk associated with nuclear radiation release are relevant to the social choice. In Figure III.12, benefit B is measured along the horizontal axis, utility U along the vertical axis. Risk aversion implies that the utility function is concave, or increasing at a decreasing rate as indicated in Figure III.12 (12). Suppose, for simplicity, that there are just two possible outcomes from the operation of a nuclear power plant: B_0, the net benefit associated with successful operation of the plant (some minimal level of radiation output), and B_1, associated with a damaging event, such as a large scale release of plutonium due to a malfunctioning of the transport or storage system. B_1 occurs with probability p, B_0 with probability (1-p). Then expected net benefits are $\bar{B} = pB_1 + (1-p)B_0$. If the individual's behavior satisfies a reasonable set of axioms, his utility from this risky

Figure III.12



prospect is $\bar{U} = pU(B_1) + (1-p)U(B_0)$, which lies directly above $\bar{B}$ on the straight line joining the points $U(B_1)$ and $U(B_0)$ on the utility function. The assumed (concave) shape of the utility function, indicates that this is just equal to the utility associated with the certain benefit $B^* > \bar{B}$. In other words, the individual puts a value on the nuclear project that is less than its expected net benefit. Finally, for given $\bar{B}$, the greater the spread in outcomes, the larger the divergence of B^* from B. The greater the potential damage, that is, the less adequate is expected net benefit as an indication of the value of the project.

There is also a kind of synergism between such uncertainty and irreversibility mentioned earlier. As one would expect, where the consequences of a project would be difficult or impossible to reverse, and their magnitude not certain, there is in effect an extra cost to the project: a loss of "option value" (14). Option value may be understood in the following way. Suppose the passage of time will result in new information about the benefits and costs of, say, a system of nuclear fission plants. The information can, however, be taken into account in energy planning only if irreversible commitments, for example the storage of radioactive waste, have been avoided. Since the accumulation of these wastes (we assume) is irreversible, once the nuclear plants are operating the consequences of a decision to put them in operation cannot be undone, even by new information which suggests the decision was a mistake. An option has been lost. Alternatively, when 10^n barrels of oil have been converted to water and carbon dioxide, the option to use that amount of oil for any reason whatsoever is also lost. But it should be emphasized that, not the fact, but rather the consequences, of irreversibility or option loss are important.

We now turn briefly to the question of how to evaluate changes in the incidence of death, disease, injury, and so on, that might be expected to accompany a project. As discussed in Section 4, the conceptually appropriate measure here appears to be the value the individual attaches to the change in the probability of the adverse event occurring. Information on this value is not easy to come by. One recent study (15) infers it from the estimated relationships between occupational wages and safety. Post attempts to measure the value of loss of life or serious injury or disability have generally been based on foregone earnings, plus direct medical expenditures. As we shall suggest, there are problems with this approach. The first, and most serious, is that it is not derived from the measure we have taken to be correct in principle, the value (paid or received) associated with full knowledge of the change in probability. Let us lay aside this objection for the moment, and explore further this technique and another, based on insurance behavior of individuals.

If it is known that operation of the project will entail a net change p, $0<p<1$, in the probability of an adverse health effect for each member of the exposed population, then the expected health cost to each can be written

as $E(c) = p \sum_{t=0}^{\infty} \frac{Y_t}{(1+r)^t}$, where Y_t represents foregone earnings in period t, and r is the discount rate. The aggregate expected health cost is the sum over all members $E^n(c) = p \sum_{j=1}^{n} \sum_{t=0}^{\infty} \frac{Y_t^j}{(1+r)^t}$, where the number of members is n. Refinements allowing the probability of the adverse effect to vary with age, date of exposure, degree of exposure, and so on, are easily incorporated, as in the measure $\sum_{j=1}^{n} \sum_{t=0}^{\infty} \frac{p_j \; Y_t^j}{(1+r)^t}$, which introduces different probabilities for each individual.

Another measure of the value of life, or avoidance of injury, that has been suggested (16) is derived from the amount an individual pays to insure against a loss, say his life. For example, if he is willing to pay a $100 premium in a situation in which the probability of loss of his life is .001, it is inferred that he values his life at $100,000 (=$100/.001).

As Mishan (17) has demonstrated, there are problems with each of these measures (and others, essentially refinements of them) apart from their arbitrariness. First, the foregone earnings measures assume that the only thing that matters to an individual or to society is the (reduction in) size of the Gross National Product (GNP). No allowance is made for the loss of utility due to pain, injury, or death. This omission is particularly serious in the case of an elderly or retired person, one for whom all remaining Y_t terms are zero. A somewhat similar problem arises in connection with the life insurance calculation: a person with no dependents might not be willing to pay anything for insurance, yet still set a value on his own life.

Second, the treatment of uncertainty is not persuasive. Suppose an individual values an object at $X, but believes the probability of loss or destruction is p. The expected loss is then $pX. If the individual were neutral toward risk, he would be willing to pay an insurance premium just equal to the amount of the expected loss. If, however, he were averse to risk, he would pay more: the expected loss plus a premium (to the insurance company) for bearing the risk. The situation is exactly as in Figure III.12, where the expected loss (from an initial level of welfare B_0) can be represented by $B_0 - \bar{B}$, and the risk premium by $\bar{B} - B^*$. Taking an expected value of foregone earnings then underestimates the value of the expected loss in earnings. Similarly, the insurance calculation of the value of life or limb described above simply reverses the procedure, while retaining the implausible linearity assumption.

From preliminary discussion, two tentative conclusions might be drawn. 1) Even if we can legitimately accept (or ignore) the distributional effects of a program involving radiation exposure, including the inter-generational effects, measurement of the expected value of the costs of the exposure will not capture the full value of the costs, due to the risk preferences of the affected individuals. 2) The unusual time distribution of the costs and their potential magnitude raise serious questions about the appropriateness of following standard practice, discounting all benefits and costs and looking only at their present values.

E. Ethics and Benefit-Cost Analysis

The general thesis in the use of benefit-cost analysis as one of the bases in the making of decisions affecting the public is that such analysis provides one of the objective evaluations on which such decisions should be based, in preference to subjective bases such as those which may derive from intuition, ideology, or political pressures.

In order to compare costs and benefits adequately in benefit-cost analysis, it is necessary to express them in common, comparable terms. Monetization is virtually the only way to arrive at common, comparable terms for summation of various kinds of benefits and summation of various kinds of costs ("costs" including risks to health and life and other usually non-monetized detriments). The value of goods or services is usually defined by "the market" and usually represents the social consensus of the value of the commodities, except perhaps for governmental or private monopolistic price regulations or externalization of costs. Even things which cannot really be valued adequately in the market place, such as a human life or a scenic view, can be assigned a monetary value based upon what people normally pay for them in various ways and circumstances.

Not the least of the arguments in favor of monetization of costs and benefits in benefit-cost analysis is that it is nearly universally accepted in our society. However, there have been severe criticisms of benefit-cost analysis because of the materialistic implications of monetization (18).

It can be also argued that a problem of using economic principles alone is that they may not be adequate to ensure future human welfare. This is in contrast, for example, to most systems in nature which have effective feedback mechanisms to prevent excessive growth and its deleterious consequences. Since our environment is limited, it is desirable that our systems, including our economic system, have adequate mechanisms of limitation which are sufficiently sensitive to react in time to avert deleterious consequences.

Another of the problems of simple benefit-cost analysis is the disproportionate or inequitable accrual of benefits and costs among people.

In its present state, the methodology of benefit-cost analysis is not adequate to guide reasonably equitable distribution of benefits and costs in major societal activities. The limitations of a purely monetary value system and of a simplistic benefit-cost analysis for the purpose of equitable distribution of benefits and costs, indicates that additional factors, mostly relying on value judgments, are required for societal decision-making. It is usually not possible to foresee and quantify all future consequences of a particular major decision of action. The interactions of events, people, and institutions are so complex that quantification and formulation of all factors is beyond currently foreseeable expectations. Furthermore, it appears that people generally view the near term as more important than the long term, so that benefit-cost analysis has tended accordingly to focus more on the near-term and discount the long-term factors.

All of this illustrates that benefit-cost analysis cannot be absolutely complete and cannot, except in simple cases, determine what is best for the whole system. For example, with an issue as complex as the present energy-environmental problem, the prospect that a simplistic application of benefit-cost analysis will yield a complete and definitive basis for decision-making appears to be untenable. One of the main reasons for this is the difficulty of assessing the impact of the decisions which might be made on future generations of people.

Thus, it is apparent that we are faced with a dichotomy. On the one hand, traditional benefit-cost analysis seeks to maximize human welfare primarily through increasing economic well-being: a process which weights heavily both material possessions and the current generation. On the other hand, a different method could be constructed upon a value system which places primary emphasis on future generations. Deciding between these systems, or how much weight each should receive, is a difficult task, about which honest people will differ passionately, since human values of an aesthetic and moral nature are involved.

We believe that both systems are important, and that in many of the complex decisions facing our society both should be used in the decision-making process. We believe that it is in the interests of the whole system (present and future) that the two approaches be brought together. This is not to dilute or modify either side, but to recognize them as partners each capable of supplying input into the decision-making process.

How can these two systems be brought together? Our philosophy throughout this volume is that it can be done through a benefit-cost analysis which goes considerably further than that developed and used in traditional economics. In decisions that have a component that depends on human values, we propose the following:

(i) The terms on both sides of the equation be given a monetary value based on the market place, public survey or other appropriate means. We acknowledge the problems, discussed above, inherent in this approach, but feel that if benefit-cost analysis is to be done at all, money appears to be the only common denominator that can be used.

(ii) Weighting factors should be applied to those terms which may be undervalued by market place economics. Typically, these are likely to include the terms which have a component which involves people not able to take part in the decision-making process.

(iii) The values of the weighting factors have to be established by society in general, whether through the political process, public survey, or other means.

The following is quoted from a recent NAS report (19):

> Benefit-cost analysis, at least as we use the term, is not a rule or formula which would make the decision or predetermine the choice for the decision-maker. Rather, it refers to the systematic analysis and evaluation of alternative courses of action drawing upon the analytical tools and insights provided by economics and decision theory. It is a framework and a set of procedures to help organize the available information, display trade-offs, and point out uncertainties. In this way, benefit-cost analysis can be a valuable aid; but it does not dictate choices, nor does it replace the ultimate authority and responsibility of the decision-maker.

The problem of incorporating both of the traditionally separate value systems into the decision-making process is perhaps the major question of the coming decades. The short- versus the long-term trade-offs depend on the manner of incorporation of the traditionally separate value systems into the decision-making process.

CHAPTER III

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CHAPTER IV

LEGAL AND INSTITUTIONAL ASPECTS OF USING BENEFIT-COST ANALYSIS TO CONTROL IONIZING RADIATION

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CHAPTER IV

LEGAL AND INSTITUTIONAL ASPECTS OF USING BENEFIT-COST ANALYSIS TO CONTROL IONIZING RADIATION

Summary

This chapter provides an evaluation of the legal and institutional issues which attend the uses of benefit-cost analysis for regulatory decision-making on ionizing radiation.

In an introductory section, the purpose and scope of the chapter, its focus on nuclear power, and basic functions of federal and state agencies are discussed.

This is followed by an analysis of the legal framework for controlling ionizing radiation from nuclear power plants and other sources in the uranium fuel cycle. The analysis is focused on the statutory authority and regulatory programs of the Nuclear Regulatory Commission, the Environmental Protection Agency, and various state agencies. Such an analysis must reflect value judgments made by the authors on the degree to which agencies have used their authorities in carrying out their responsibilities and the manner in which they have done so.

The third section contains an evaluation of the analytical methods and decision-processes employed by such regulatory agencies to establish specific design and performance requirements for nuclear power plants and offsite environmental and health standards.

The final sections of the chapter include discussion of basic legal and institutional considerations arising from uses of benefit-cost analysis in regulation and conclusions applicable to the formulation of national policy and federal programs for toxic and carcinogenic pollutants including, but not limited to, ionizing radiation.

CHAPTER IV

LEGAL AND INSTITUTIONAL ASPECTS OF USING BENEFIT-COST ANALYSIS TO CONTROL IONIZING RADIATION

A. Introduction

1. Purpose and Scope of Chapter

As other chapters of this report have indicated, most human exposure to ionizing radiation from artificial sources is attributable to medical uses. Nevertheless, in this chapter, assessment of the use of benefit-cost analysis in the control of ionizing radiation focuses primarily on the nuclear energy fuel cycle for several reasons:

- Regulation of ionizing radiation, employing benefit-cost analysis, has occurred only within the context of the nuclear energy fuel cycle.
- Regulation of nuclear energy is substantially centralized in a single federal regulatory agency; therefore, use of benefit-cost by such agency can be socially assessed by the criteria of administrative law, which have been designed to ensure accountability of agency decision-making.
- The number of nuclear power reactors in the U.S. is expected to increase significantly. Regulatory problems should be identified and addressed immediately, since the pattern of regulation will become increasingly difficult to change as the commitment grows, and larger societal and economic interests are threatened by change.
- Each reactor represents a continuing source of long-lived radionuclides which accumulate in the environment, and therefore constitutes an important dose commitment for present and future generations.

As a result of these considerations, this chapter focuses on the nuclear energy fuel cycle for purposes of assessing the uses of benefit-cost analysis in decision-making on ionizing radiation. The balance of this introductory section briefly describes the nuclear energy fuel system and radiation control options.

2. Nuclear Power Case Study

Ionizing radiation, as a form of pollution, can be depicted by a simple flow-chart or model to facilitate analysis of the relative roles of various regulatory authorities at federal and state levels. A basic model, employing a nuclear power plant for illustration, can be presented (Figure IV.1).

A coherent approach to the regulation of ionizing radiation from nuclear power sources calls for consideration of the nuclear fuel cycle; and more detailed flowcharts or models can be developed to depict this cycle and the array of authorities and their roles in controlling radiation. A more detailed model is now presented to provide a more complete context for assessing the regulation of ionizing radiation (Figure IV.2).

The diagrams demonstrate that four primary types of authorities function to control ionizing radiation arising from the use of nuclear fuel in the operation of a nuclear power plant.

These authorities (Figure IV.2) are:

(1) Site, Construction and Design Controls: Site---The states and their local subdivisions control the use of private lands and non-federal, public lands: and the federal agencies (e.g., Dept. Interior) similarly control federal lands. Nuclear Regulatory Commission siting guidelines establish criteria necessary for its approval of proposed sites.

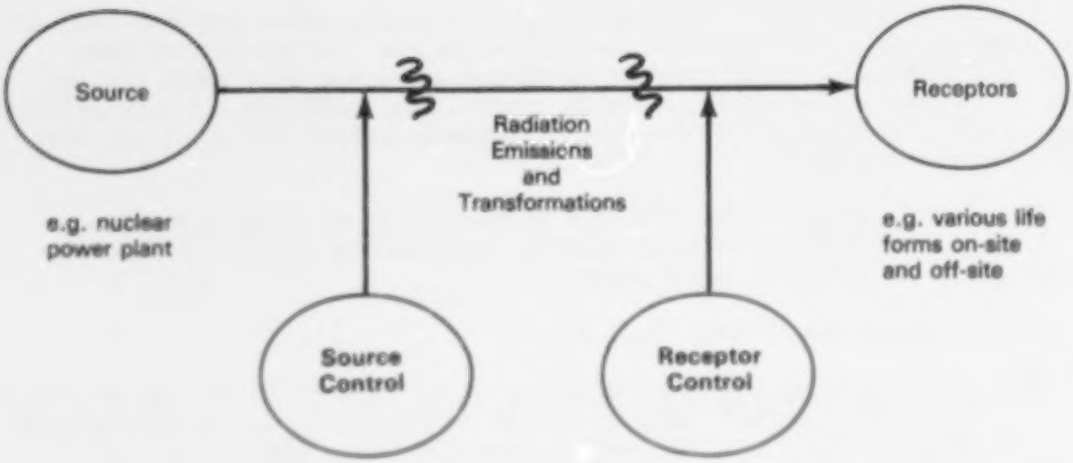
Construction and Design---Implementation of the National Environmental Policy Act requires broad assessment by federal agencies and state authorities, with "lead agency" responsibility for assessment of most nuclear facilities in the U.S. Nuclear Regulatory Commission, and statutory responsibilities for review of assessment in the U.S. Environmental Protection Agency and Council on Environmental Quality. The Nuclear Regulatory Commission has exclusive authority to establish design standards and to issue the construction license necessary for power plant realization.

(2) Source Operation and Performance Controls---The U.S. Nuclear Regulatory Commission has exclusive authority to: establish operating and performance requirements; issue interim and operating permits; control various activities involving nuclear materials ("Source", "by product" and "special") and the disposal of wastes; and set and enforce most regulations for such activities. The U.S. Department of Transportation shares authority to control transport activities with the Nuclear Regulatory Commission (1).

(3) Onsite Receptor Controls---The U.S. Nuclear Regulatory Commission, Bureau of Mines and various State authorities control the exposure of employees and materials in the on-site occupational environment to ionizing radiation (1).

(4) Offsite Receptor Controls---Control functions are widely dispersed: The Federal Food and Drug Administration has authority over radioactivity contamination of shellfish and other foods; State and U.S. Environmental Protection Agencies have advisory and regulatory

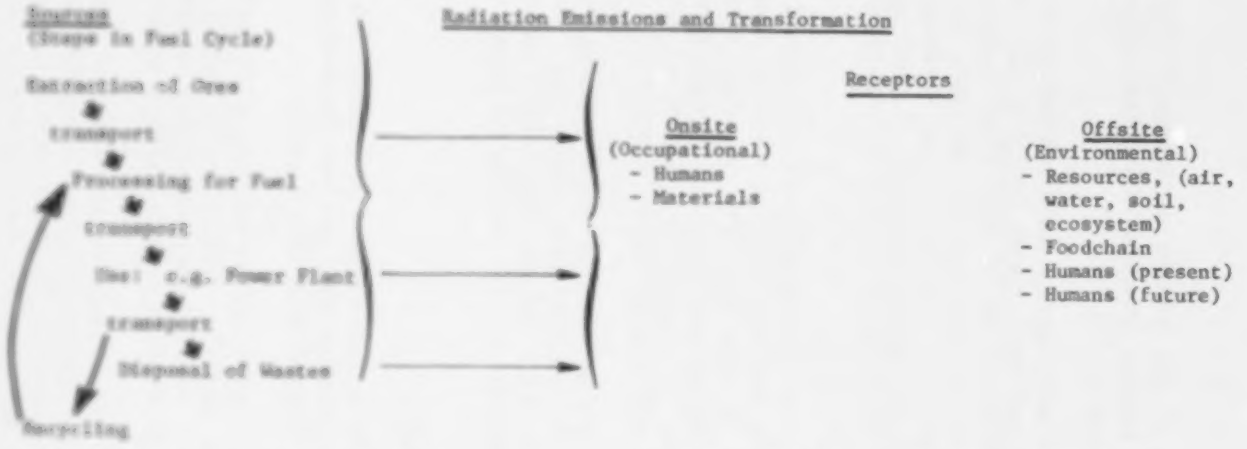
FIGURE IV.1: Radiation Pollution Control


Source
e.g. nuclear power plant
Radiation Emissions and Transformations
Receptors
e.g. various life forms on-site and off-site
Source Control
Receptor Control

Nuclear Regulatory Commission: control over design, facility discharges, etc. by means of standard-setting, permits and other regulatory processes governing source activities.

Environmental Protection Agency and State Agencies: control by means of monitoring and standard setting regarding different features of ambient, off-site environment; and review of Nuclear Regulatory Commission environmental impact statements for off-site effects: State authorities and the Nuclear Regulatory Commission regarding occupational environment.

FIGURE IV.2: Nuclear Fuel Cycle Context for Radiation Pollution Control


Sources
(Stages in Fuel Cycle)
Extraction of Ores
transport
Processing for Fuel
transport
Use: e.g. Power Plant
transport
Disposal of Wastes
Recycling
Radiation Emissions and Transformation
Receptors
Onsite
(Occupational)
- Humans
- Materials
Offsite
(Environmental)
- Resources, (air, water, soil, ecosystem)
- Foodchain
- Humans (present)
- Humans (future)

Controls: Siting, Design and Construction
Source Operation and Performance

(a) Siting: (Federal Lands) U.S. Dept. of Interior, with U.S. Nuclear Reg. Commission.

(b) Siting: (State and Private Lands) State and Local Siting Boards, Zoning Authorities, Energy Commissions, with U.S. Nuclear Regulatory Commission.

(c) Construction and Design: (Environmental Impact Assessment) U.S. Nuclear Reg. Commission, Environmental Protection Agency, Council on Environmental Quality; and other State and Federal agencies

involved in site and facility analyses and consideration of alternatives under NEPA.

(d) Construction and Design: (Standards) U.S. Nuclear Regulatory Commission.

(e) U.S. Nuclear Regulatory Commission (with U.S. Department of Transportation re transport controls).

Controls: Onsite Receptors, Offsite Receptors

(a) State Occupational Safety and Health Agencies and U.S. Nuclear Regulatory Commission

(b) U.S. and State Health, Fish and Wildlife Authorities

(c) U.S. Environmental Protection Agency, Public Health Service, Food and Drug Administration functions for various features of the ambient environment such as water, air, soil, animals, and humans (present and future generations); and for public water supply (1).

This chapter focuses primarily on federal agency decision-making related to Design Controls (1), Source Operation and Performance Controls (2), and Offsite Receptor Controls (4), as such controls are of most significance to the direct regulation of radiation, the use of cost-benefit analysis to establish limitations, and the implementation of the "As Low As Reasonably Achievable" (ALARA) concept. Site, and Construction Controls (1) and Onsite Receptor Controls (3) are also important elements of radiation regulation, and are discussed in this chapter.

Figures IV.1 and IV.2 emphasize the time development of the system they describe, and illustrate key points in the fuel cycle where various regulatory agencies and other authorities intervene in order to carry out their statutory duties. This overall, integrated view will subsequently be disaggregated to enable more detailed examination of radiation regulation by means of cost-benefit analysis and the "As Low As Reasonably Achievable" concept.

The following diagram (Figure IV.3) summarizes the relationships between the three major authorities involved in the nuclear fuel cycle--the U.S. Environmental Protection Agency (EPA), the U.S. Nuclear Regulatory Commission (NRC), and the States--and their relationships to the utility or power plant proprietor.

Two structural issues are now apparent:

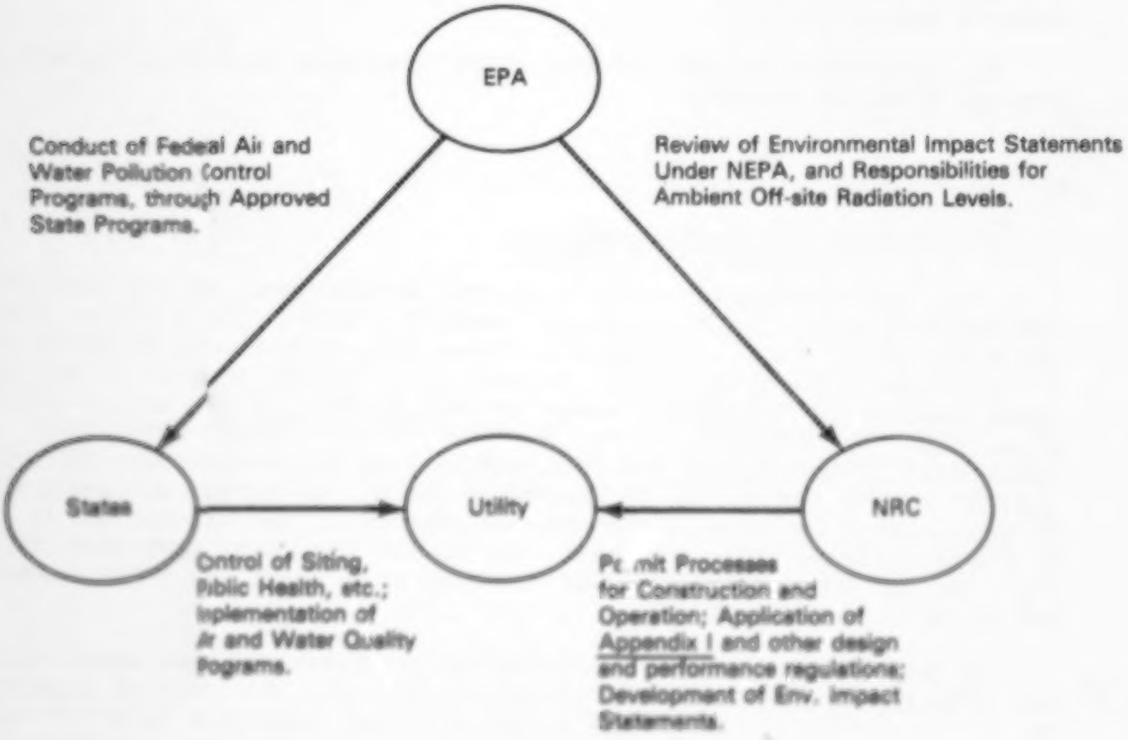
(1) EPA does not act directly on the actual source of radioactive emissions, but acts through other agencies that may not understand, or be able to implement, or may disagree with EPA's goals.

(2) The two paths of authority converging on the utility give rise to potential difficulties (a) when mutually exclusive and conflicting orders are given to the utility, and (b) when no agency or interagency mechanism is available or willing to deal with a problem.

In the second part of this chapter, the ability of the present institutional structure to carry out regulatory responsibilities involving benefit-cost analysis and the ALARA concept is assessed. This assessment includes analysis of the authority granted to key agencies by their governing statutes, the duties and discretion involved in the exercise of agency authority, judicial decisions construing such statutes, the overlap of various grants of authority, and gaps that may exist in coverage where no agency presently can or will act--all with respect to determining the efficacy of this structure for effectively regulating radiation.

In the third part of this chapter, decision-making that occurs within this institutional structure is assessed. This analysis includes review of the uses of benefit-cost analysis and the ALARA concept by the authorities in their decision-making on standards and other elements of regulation;

FIGURE IV.3: Regulatory Authority Structure


EPA
Conduct of Federal Air and Water Pollution Control Programs, through Approved State Programs.
Review of Environmental Impact Statements Under NEPA, and Responsibilities for Ambient Off-site Radiation Levels.
States
Utility
NRC
Control of Siting, Public Health, etc.; Implementation of Air and Water Quality Programs.
Permit Processes for Construction and Operation; Application of Appendix I and other design and performance regulations; Development of Env. Impact Statements.

whether cost-benefit and ALARA are to be understood as applying on a case-by-case or generic basis; and measures of accountability imposed on agency decision-making by judicial review.

This assessment stage is concerned primarily with the adequacy of the analytical processes employed for decision-making by the agencies in the context of administrative law. Particular findings or standards that result from the processes, and the competence and availability of the personnel to carry out the processes, are beyond the scope of this chapter.

The fourth part of this chapter presents basic legal and policy issues inherent in the use of benefit-cost analysis for agency regulation and judicial decision-making.

The fifth and final part of this chapter contains conclusions derived from the foregoing analyses.

B. Institutions and Authority

1. Nuclear Regulatory Commission

From 1954 to 1970, authority to control nuclear power and its externalities was concentrated in the Atomic Energy Commission (AEC). The statutory grant was broad, giving the agency power to impose such conditions on licensees as it determined to be in the public interest (2). The AEC chose to follow the recommendations of the Federal Radiation Council (FRC)(5) as a policy decision. It was not compelled to do so, as FRC authority was limited to providing "guidance," (3) and the AEC had full authority to act independently (4). The standard recommended in 1960 by the FRC of 500 mR. to the most exposed member of the public was adopted by the AEC, included in its regulations, and is still in effect under the AEC's successor, the Nuclear Regulatory Commission (NRC) (5). The FRC was abolished and its functions transferred to the Environmental Protection Agency in 1970 (6).

In 1970, when the Environmental Protection Agency (EPA) was established, the authority of the AEC to set "generally applicable environmental standards for the protection of the general environment from radioactive material" was transferred to EPA by Reorganization Plan No. 3 (7). The term "standards" as used, was also defined:

> ...standards mean limits on radiation exposures or levels, or concentrations or quantities of radioactive material, in the general environment outside the boundaries of locations under the control of persons possessing or using radioactive material (7).

AEC authority to impose conditions on its licensees was therefore retained but modified, in the sense that conditions which related to offsite radiation levels and exposures would henceforth have to be consistent with EPA regulations and guidelines.

At the time this change occurred, the AEC adopted as its policy another FRC recommendation for maintaining "radiation exposures and releases of radioactive materials...as far below the limits specified...as practicable" (8). This policy is the conceptual source for significant features of subsequent AEC regulation of its licensees, such as the AEC's Appendix I (9), which provides "numerical guides for design objectives and limiting conditions for operation to meet the criterion 'as low as is reasonably achievable' for radioactive material in light-water-cooled nuclear power reactor effluents" (10). Following a four and a half year gestation period in "proposed" regulation status, a final version of Appendix I was promulgated by the Nuclear Regulatory Commission on April 30, 1975 (10).

The Nuclear Regulatory Commission (NRC), successor to the AEC in most nuclear power regulation respects, attached a condition to its final decision on Appendix I: Appendix I does not provide numerical standards or criteria, but serves to give license applicants "qualitative guidance" as to "one acceptable method of establishing compliance with the 'as low as is reasonably achievable' requirement;" and the applicant is free to persuade the NRC that some alternative design or method would constitute "as low as is reasonably achievable" (ALARA)(11). As a practical matter, the high cost of such a persuasion attempt and the low probability of success make this an unrealistic option for most applicants. Therefore, the NRC has been relatively free to develop ALARA standards in its promulgation of Appendix I (12).

The legal issue in this matter relates to agency accountability when judicial review of agency rule-making is sought. Judicial review can focus on procedures used in the promulgation of such rules of general applicability, and on the substantive merits of the rule in question. Since judicial review of a "guidance" is not as rigorous as review of a standard would be, particularly where the guidance expressly allows the consideration of alternatives to be presented by applicants, the NRC is thereby less accountable on Appendix I than it is on more conventional rules and standards. The agency has thereby reserved substantial discretion on the matter of numerical limitations for implementing ALARA, and therefore remains fully accountable only to the 500 mR. limit it adopted as a standard following the 1960 recommendation of the FRC.

A related legal issue involves the validity of AEC adoption of the ALARA concept for use in regulating facility design and operation, and thereby the validity of NRC's Appendix I for quantifying and applying ALARA in practice. If ALARA and Appendix I could be construed as providing for "generally applicable environmental standards for the protection of the general environment from radioactive material," the AEC would lack authority for such adoption, since the transfer of such authority to EPA occurred on December 2, 1970 (13). Consequently, NRC enactment of Appendix I would be beyond the agency's scope of authority.

The practical effect of the foregoing developments has been the continued and extensive involvement of the AEC, and now the NRC, with decision-making and assumptions about offsite radiation levels and exposures, and the incorporation of such determinations in NRC licensing and other onsite regulatory decisions--coincident with EPA's substantial silence on offsite radiation matters, despite the authority it has had since the 1970 Reorganization Plan.

EPA has agreed to the continued NRC role; has not sought to systematically provide data and opinions on offsite radiation levels and exposures to the NRC and the states; and in 1975 circumscribed its own role to that of setting the outer boundary or parameter for uranium fuel cycle radiation in the general environment (14)--within which the NRC could establish new ALARA numbers and modifications of existing regulatory requirements (15). This EPA proposed regulation is not restrictive in regard to present plant emission levels, and would thereby leave to NRC discretion most facility-specific decisions as to whether and when lower emission levels should be required of licensees. Thus, the objective of the Reorganization Plan to have EPA develop ambient and other offsite requirements for radiation, and to thereby play a central role in facility-related decision-making by the NRC, has not been realized. As a result, the NRC, alone, has determined desirable offsite levels and exposures, and incorporated them at its discretion in the conditions it imposes on licensees.

2. Environmental Protection Agency

The transfer of radiation authority from the AEC to EPA was part of a general plan to consolidate environmental control programs at the federal level, to establish EPA as the overall coordinator of pollution control efforts, and to put "...into one agency a variety of research, monitoring, standard-setting and enforcement activities scattered throughout several departments and agencies" (15).

Subsequent laws, such as the Clean Air Act (CAA)(16) and the Federal Water Pollution Control Act Amendments (FWPCA)(17) provided EPA with explici pollution control objectives, means and enforcement responsibilities; they also charged EPA with the responsibility for determining feasible control measures for various sources and types of pollution. Further, these laws also provided the criteria to be used in EPA decision-making on permissable discharge levels from different classes of sources and on ambient levels of pollutants for air and water (18). The implications of these two pollution control programs for the regulation of radiation from power plant sources, and for the use of cost-benefit analysis and ALARA in decision-making, are discussed in subsequent sections of this chapter.

EPA has not played an integral role in NRC's regulation of power plant design and operation, despite the broad authority conferred by the Reorganization Plan on EPA for setting "generally applicable environmental standar for the protection of the general environment from radioactive material" (1 and despite the obvious connections between emissions at the source (controlled by NRC) and the offsite levels of radiation (EPA responsibility).

Responsibility for this limitation of EPA's role stems to some extent from the Office of Management and Budget (OMB) and the Executive. In a memorandum from OMB to the EPA dated December 7, 1973, the following directive was contained and accepted by EPA.

> ...this memorandum is to advise you that the decision is that AEC should proceed with its plans for issuing uranium fuel cycle standards, taking into account the comments received from all sources, including EPA: that EPA should discontinue its preparations for issuing, now or in the future, any standards for types of facilities; and that EPA should continue, under its current authority, to have responsibility for setting standards for the total amount of radiation in the general environment from all facilities combined in the uranium fuel cycle, i.e., an ambient standard which would have to reflect AEC's findings as to the practicability of emission controls....

EPA was thereby directed to limit its activities to the setting of general environmental standards, and further directed to set such standards in conformance with AEC determinations as to the economic and technical feasibility of available source control measures. It should be noted that environmental limitations on other toxic and hazardous pollutants, for example, those subject to regulation under the air and water pollution control laws, are usually required to be established primarily on the basis of environmental and health effects, rather than on the basis of economic and technical feasibility (19).

Offsite, or general environmental, radiation levels and exposures can be controlled most effectively through restrictions on the siting, design, and operation of new sources;and through backfitting and other design and operational requirements on existing sources. (See Introduction and Figures IV.1 and IV.2.) Therefore, a coordinated effort at radiation control, involving the EPA, NRC, and the States, would be necessary if either agency wants to meet fully its responsibilities for environmental quality and human health.

These responsibilities are manifest in judgments that should be made for regulating radiation, such as:

a) Acceptable environmental levels and exposures (EPA, with local and State health inputs);

b) Optimal locations or sites for emitting sources (EPA, NRC, and primarily the states);

c) The "dose commitment" that should be allocated to existing and new sources over the long term (20)(EPA, NRC, and federal and state authorities responsible for energy growth and new facility approvals);

d) The technical and economic feasibility of the control measures and design features of power facilities, necessary to meet offsite objectives (NRC, EPA); and

e) The consistent reduction of emission levels and exposures called for by the ALARA concept; through new "control technology--forcing" standards and modifications of prevailing requirements, as justified by the balancing of costs and benefits attributable to the reductions being considered, and by the feasibility of the technologies to be utilized (EPA, NRC).

EPA's achievements to date in this area have been limited primarily to articulation of the "dose commitment" concept (20) and the announcement in 1975 of proposed, generally applicable environmental standards for radiation levels and exposures related to the uranium fuel cycle (14). The standards proposed by EPA are relatively high, and far greater than current radiation levels associated with presently operating facilities; this leaves to the NRC discretion in imposing conditions on new and existing facilities (21)--provided that the levels arising from any source do not exceed the EPA upper limits, an unlikely event. This issue and the various levels as quantified are discussed further.

Neither the NRC nor EPA has chosen to use ALARA as a dynamic regulatory principle which would constantly force on NRC licensees the requirement to further limit emissions in the public interest, as such further limitations are justified by offsite radiation levels (which may accrue from sources other than the particular facility in question); and as justified by improving conditions of technological and economic feasibility for more stringent emission controls. Nor has EPA played any role in the formulation of criteria and guidances for optimal site selection as another means of implementing ALARA and improving overall regulation of environmental radiation. EPA has therefore complied fully with the OMB memorandum discussed above, and Congress has not determined whether this executive branch determination accords with Congressional enactments and legislative history, and with the public health and welfare.

Discussion of these matters immediately raises the issue of EPA discretion. EPA inherits its basic authority from the FRC and the AEC through the *Reorganization Plan* (7), and as a matter of course, the discretion and duties that accompany that authority. The original authority provided the FRC to "guide" the agencies (22) does not impose any duty on EPA to become involved in the regulation of facility siting, design and operation, nor to participate in the implementation of ALARA. However, the original grant of authority to the AEC (23) established an AEC duty to set and implement standards as required by the public interest; thereby indicating that EPA, as heir to this duty, should now be playing a key role in carrying out the several regulatory tasks outlined above.

Although the *Reorganization Plan* discusses standards only in terms of their general applicability, the EPA role, of necessity, must also involve regulation of a facility-specific nature when extraordinary or exceptional circumstances surrounding a site, a plant's operation, or actual offsite levels render the generic approach inadequate to provide for the public interest. Certainly, this facility-specific regulatory role is not precluded by the terms of the *Reorganization Plan*. Nevertheless, EPA has adopted standards approach of general applicability only, and has left facility-specific regulation to the NRC (14).

By an independent route, EPA has been involved with the review of specific facility proposals of NRC applicants. The National Environmental Policy Act (NEPA) (24) and Guidelines of the U.S. Council on Environmental Quality (25) provide that EPA and other agencies with jurisdiction or special expertise review environmental impact statements (EIS) including those done by the NRC at the construction and operating permit stages of power plant approval. This EIS review role has been made mandatory for EPA by section 309 of the Clean Air Act, which requires EPA to review the actions of other federal agencies, as embodied in their EIS's, from "public health" and "environmental quality" perspectives, and to report problems to the Council on Environmental Quality (26).

This is adequate authority for EPA review of and public comment on specific facility proposals in virtually all pollution respects, including radiation and the implementation of ALARA in the siting, design and future operations of the facility. Nevertheless, EPA's position on the radiation aspects of such review has been to rest content with its recently announced proposed standards of general applicability. If EPA formally adopted ALARA, its review of the EIS's done on nuclear power and fuel cycle matters could be a means of implementation of this important concept on a facility-specific basis.

The EPA also possesses authority under the Clean Air Act (27), the Federal Water Pollution Control Act (FWPCA) (28) and the Safe Drinking Water Act (SDWA) (29) that could involve it further with radiation discharges and off-site levels. SDWA requires EPA to issue regulations for "contaminants" which have been defined to include radiological materials (30); the Clean Air Act requires EPA to regulate pollutants that are determined by the Administrator to be hazardous to public health (31); and the FWPCA requires that EPA (1) regulate the discharge of water pollutants from point sources, including the discharge of radioactive materials (32), (2) establish effluent (discharge) standards for toxic pollutants (33), and (3) approve appropriate water quality (ambient) standards to be established by the states (34).

These statutes provide specific duties and less discretion to the EPA than its inherited AEC authority, in that they require EPA to act, provide explicit criteria for agency use in regulation, impose time limits, and provide for citizen suits and judicial review.

EPA has not implemented the Clean Air Act and the FWPCA insofar as they apply to releases of ionizing radiation from nuclear power plants, maintaining that responsibility for regulating such releases into air and water rests with the NRC. To maintain this position of deference to the NRC with regard to releases into water, EPA appealed a decision of the U.S. Court of Appeals for the 10th Circuit, Colorado PIRG v. Train (35), to the U.S. Supreme Court. In the decision of the Court of Appeals, EPA was ordered to set effluent standards for the discharges of radioactive waste water from nuclear power plants, in accordance with the Court's interpretation of the regulatory responsibility imposed on EPA by the FWPCA--which statute includes "radioactive materials" in its definition of pollutants subject to EPA control by means of effluent and ambient limitations. The Supreme Court, in reversing the Court of Appeals (36), accepted EPA's argument that the regulation of such effluents is a responsibility which rests with the NRC, under prior Atomic Energy legislation (37), and that EPA's radiation discharge responsibilities under FWPCA relate only to the release of "other" radioactive materials such as radium and accelerator-produced isotopes (38).

The Supreme Court's decision thereby constitutes a limitation on EPA's use of its statutory authority to control an important pollution problem at the source, and has created an exception to the otherwise all-inclusive scheme for water pollution control as designed by the Congress in the FWPCA--a scheme which requires EPA to regulate (1) electric generating facilities as "point sources" (39); (2) "radioactive" effluents (40); (3) other wastewater discharges of a polluting nature (e.g., thermal, anti-corrosion chemicals, etc.) from nuclear plants (41); and (4) toxic materials (42). Since EPA is carrying out most of these other tasks and could develop interagency mechanisms for drawing on NRC radiation expertise, there should not have been any administrative or technical difficulties in extending its program to radiation discharge regulation. EPA, therefore, appears not to have undertaken any regulatory functions of significance with regard to ionizing radiation.

3. The States

The states are involved with EPA, as noted above, in carrying out the requirements of the Clean Air Act, FWPCA, and the Safe Drinking Water Act, all of which require EPA approval of state implementation plans, review of subsequent state performance, and EPA action upon state default (43). However, in light of the Supreme Court's decision in Colorado PIRG (36), regulation of waterborne discharges from nuclear power plants rests with the NRC, and neither EPA nor the states through their FWPCA programs under EPA authority have authority to regulate such wastewater discharges. Further, any independent role for the states in controlling such wastewater discharges, has been excluded as a result of the decision of the U.S. Supreme Court in Northern States Power Co. v. Minnesota (44). In this decision, the Supreme Court affirmed a circuit court ruling that the regulation of such discharges from power plants is a federal responsibility, as a result of federal preemption established by the Atomic Energy Act of 1954 and the subsequent scheme of federal legislation and regulation. Colorado PIRG and Northern States would also appear to provide a basis for excluding any EPA or state role in regulating airborne discharges of ionizing radiations under the Clean Air Act or other authority, on the basis of the Supreme Court's findings in these decisions as to Congressional intent, although cases on the air discharge issue have not materialized to date. Therefore, the states have no apparent opportunity to directly control discharges of ionizing radiation from nuclear power plants into the air and water.

However, the general authority of the states under the Constitution (45) to protect public health, safety and welfare has provided a basis for state authority in determining acceptable levels of radiation in the offsite environment. State and local authorities have established various criteria and standards relating to offsite exposure and ambient levels of radiation (46). On this basis, and consistent with the ambient water quality provisions of the *FWPCA*, several states have also developed radiation standards and criteria for ambient water quality as part of their effort to achieve water quality objectives (47). This activity has not been challenged in the courts, and such regulation of offsite, ambient levels would seem to fall outside the scope of federal preemption defined in Northern States, and outside the scope of NRC authority defined in *Colorado PIRG*, since both cases dealt with the issue of a direct attempt to regulate waterborne *discharges* by agencies other than the NRC (48). Therefore, if the states have any role in regulating ionizing radiation, it is founded on their "police power" and consists of their ability to regulate the offsite environment for purposes of protecting public health, safety, and welfare.

Finally, the states have their land use authority, under the regulatory powers conferred by the Constitution, to further provide for public health, safety and welfare at state and local levels. In addition to zoning and subdivision control methods of regulating land use, many states now provide for special board and procedures to govern the siting of major facilities, such as power plants and transmission lines.

The NRC has no express authority to acquire power plant sites for utilities, nor does it have authority to change or override state and local laws governing land use, but is limited to considering the suitability of those plant sites proposed by applicants for plant construction licenses. Applicants must, therefore, acquire title or lease to sites, and conform to use restrictions, under prevailing state and local laws; in addition to securing NRC approval and construction permit under NRC regulations and guidelines which have been promulgated to insure public safety.

States have the opportunity to restrict or confine radiation hazards at the pre-construction, site-review stage. The implications of this growing state role, demonstrated by the creation of energy facility-siting boards and their use of environmental and safety criteria (e.g., in Massachusetts, New York, Maryland, etc.), are extremely significant for the regulation of ionizing radiation, irrespective of implementation of ALARA by NRC and EPA (49).

The potential for an enlarged state role in controlling ionizing radiation may be limited by (1) a lack of state resources to carry out the technical analyses necessary for safe siting (50); and (2) the traditional dependence of the states on federal agencies, primarily the AEC and NRC, in establishing regulations.

With regard to the issue of state resources, a World Health Organization assessment noted:

> While 47...states have adopted legislation...to control...ionizing radiations, there are major divergences in the implementing regulations...Only 50 percent have adopted most of the provisions of the model regulations (suggested by the Council of State Governments, and drawn up with the collaboration of the AEC and the

> PHS...eleven states have no regulations for the control of radioactive materials not subject to the Atomic Energy Act of 1954... The following are reported to be major inadequacies...(1) lack of regulations or failure to update regulations...(2) insufficient funds and personnel...(4) lack of uniformity in the control of health hazards from the use of radium and accelerator-produced radionuclides including safety standards, inspection requirements, regulations and enforcement (46).

As for state dependence on the NRC, "Suggested State Regulations for Control of Radiation" (SSRCR) have been promulgated and updated periodically following an original initiative by the Council of State Governments, the AEC, the U.S. Public Health Service and other federal agencies. The lead role has been played by the AEC, insofar as the SSRCR deals with power plant radiation, and the latest SSRCR, published in 1974 (50) also involved inputs from the Food and Drug Administration and the Conference of Radiation Control Program Directors representing state agencies. EPA was not involved in the most recent SSRCR effort.

C. Decision-Making

1. Concepts

The position that there is no safe or threshold level for human exposure to radiation has been adopted by the NRC and EPA (51). Therefore, regulation cannot be premised on achieving and maintaining a level of radiation in the ambient environment, above natural background, that is safe for human health.

In light of this position, regulation of ionizing radiation can be based on either of two approaches:

(a) total prohibition of any releases to the offsite environment from energy facilities (as well as from medical and industrial facilities), the zero-discharge approach; or

(b) allowance of releases to the offsite environment and resulting exposures only as justified by a balancing of interests, such as can be accomplished, in part, through the use of cost-benefit analysis. This so-called "rational approach" thereby provides controls on radiation levels to the extent the associated costs of control and the externalities such as damage to human health are balanced or offset by the benefits to be derived from the use of the radioactive materials; i.e., the benefit-cost approach. The analytical and ethical issues and limitations of this approach to the regulation of radiation are addressed in other chapters of this report.

The zero-discharge approach (52), which would essentially halt the construction and use of nuclear power facilities, has been rejected by the NRC (53) and ignored by the Congress. Therefore, subsequent discussion of regulation will focus on the benefit-cost approach now being employed (54).

There are three points implicit in the benefit-cost basis for regulating radiation:

(1) Regulation should be responsive to changes in the economics and technology of radiation control, and to new knowledge of health effects and other consequences.

(2) The balance point at the margin for costs and benefits determines the radiation level to be prescribed.

(3) Since the costs include carcinogenesis and genetic mutagenesis as health effects, the latter occurring over several generations, whose significance cannot be quantified at values acceptable to all in society, the task is not amenable to traditional or formal benefit-cost analysis. Nevertheless, the benefit-cost structure or procedure should be used to the extent possible to provide for as rational a decision-process as possible. These "unquantifiable" variables, or rather, "arbitrarily-quantifiable" variables should therefore be identified by the regulators and exposed to some form of open, participatory process of quantification; since quantification of all variables is ultimately necessary for conducting the benefit-cost process.

These points are made in recognition of various factors which may be included in the regulatory process to consciously distort the benefit-cost analysis for purposes of enhancing public health and safety, such as: (a) the use of safety or weighting factors in light of uncertainties about information, or in light of significant public concerns and fears; and (b) the payment of a premium above the minimum total cost to society for purposes of providing additional protection to a particularly exposed group such as those who live in the environs of a power plant. The use of such factors should be articulated and subject to review outside the agency.

The benefit-cost approach has been adopted by the NRC for purposes of setting radiation regulations, and reinforced by NRC adoption of the general principle that radiation exposure to the public should be kept "as low as is reasonably achievable (ALARA), or as ALARA has been formally defined:

> as low as is reasonably achievable taking into account the state of technology, and the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to the utilization of atomic energy in the public interest (55).

ALARA therefore represents at least an affirmation of the use of benefit-cost analysis in regulation. The following discussion considers agency and judicial experience with benefit-cost and ALARA to date.

2. Nuclear Regulatory Commission

a. Pre-1975

From the time of the first commercial reactor to 1970, the AEC licensing system suffered from lack of sufficient information on the long-term health effects of ionizing radiation. Therefore, the AEC had no "rational" (cost-benefit) basis for its numerical values on radiation exposure limits, and proceeded on the basis of conservative assumptions. Disputes between AEC staff and a utility over the degree of radiation control to be imposed could only be resolved by negotiation and ultimately by AEC imposition of essentially arbitrary numerical values.

The environmental movement and public concerns over the quality of AEC regulation increased in the late 1960's; and challenges to AEC standard-setting and other aspects of AEC decision-making were brought to the courts for judicial review (56) by the early 1970's. The AEC adopted the ALAP/ALARA concept and began to incorporate it into its regulatory programs in 1970 (57), as has been generally discussed thusfar.

During the long gestation period of ALARA quantification, the 1970-1974 period during which Proposed Appendix I was employed to impose interim conditions on licensees (58), the AEC's "Staff System" operated without dollar values for health damage caused by radiation exposure, and therefore lacked a key element for cost-benefit calculation (59). Without such dollar values, the AEC nevertheless set limits for maximum individual exposures; but had no rational basis for dealing with the exposure of large numbers of people at low levels of ionizing radiation that leads to statistically-determined cases of cancer and birth defects under the linear damage hypothesis.

Control measures that would make no difference for the case of the most exposed individual, but which could be justified on the basis of cost-benefit analysis for large population exposure, were therefore not implemented. As a result, a utility could have conceivably been free to stop with its control measures once the most exposed individual limit was reached, instead of being forced to control at a level determined by a cost-benefit balance point.

Another problem with the "Staff System" arose from the condition that design calculation limits for radioactive iodine emission had reached the limits of technology. The Staff, therefore, designed a method for use on a case-by-case basis. If a proposed reactor would exceed the design limits for radioiodine, it would nevertheless be deemed in compliance if a list of specified control measures for iodine removal (Base-Line-In-Plant, or BLIP) would be installed. Since the calculations were conservative, and there was no dollar value for radiation exposure, the Staff could not determine by benefit-cost analysis if such exceptions were justified. However, since old plants without such measures produce exposures much less than the 15 mR. limit for radioactive iodine, the method was based on the assumption that the public would not be exposed to undue health risk, but possibly would be exposed to excessive costs passed on through the utilities' rate structure (60).

b. 1975: New System

The NRC, in its recent ALARA opinion,(61) has modified the "Staff System" in order to correct such defects. It has assumed an interim dollar value for the societal cost of a man-rem (62), imposed a requirement of benefit-cost calculations using that figure (63), and dispensed with the BLIP feature (64). The dollar values of $1000 per total-body man-rem and $1000 per-man-thyroid-rem chosen are admittedly arbitrary and conservative, and NRC proposes to hold rulemaking hearings to set a final figure (65).

The NRC opinion retains limits on individual exposure, but adds a requirement that further measures will be required if justified by cost-benefit calculation based on the total dose to the population (66). This will eliminate the possibility that a utility would be permitted to maintain control at a level no greater than that necessary for individual limits, and presumably carries out the implication of ALARA for case-by-case pressure.

The new system, then, has an improved structure, with numbers to refer to during the design process, limits for protection of the most-exposed individuals, and clear directions for measures to reduce the population dose--measures that depend on the cost-benefit balance that is required by ALARA. However, several major regulatory issues remain, and are now discussed.

ALARA is one of the most important of numerous design factors built into NRC regulations for licensing new facilities, and also has implications for "backfitting" existing plants as well. "Backfitting" would involve the addition of radiation controls to existing plants, as justified by cost-benefit analysis, and is more expensive than installation of similar controls at the time of facility construction. NRC has left the matter for future consideration on a case-by-case basis, and has excluded any generic approach (67).

"Backfitting" also becomes a possibility for the current generation of reactors to be licensed under Appendix I, for example, where actual growth of the receptor population is markedly different from the expected population growth used in design calculations at the time of original licensing. Under such conditions, NRC has the options of either "backfitting" the plant in question or restricting its operation (68). Neither the NRC nor the states have confronted this issue of receptor population growth and its implications for plant operation, and it is admittedly a politically difficult task involving social planning and land use restrictions for the environs of plant sites.

To ensure that ALARA and other conditions are met, licensees are required to monitor their operations and provide feedback to the NRC. Data is collected on actual emissions, offsite levels, and land-use patterns in the vicinity, and such feedback to NRC should also ensure that application of ALARA-based regulations will be responsive to changes or unexpected conditions (68).

Although data collection tasks are well-defined, the overall information feedback loop from operational (actual) data to design calculation to regulatory modifications regarding controls has not functioned well from a benefit-cost perspective. NRC, EPA and the energy industry all agree that present calculational models overestimate radiation exposure--by more than a factor of ten in the case of iodine, for example (69). The ALARA concept, which implies a balance between costs and health risks, will therefore not be fully realized until NRC develops design calculations that incorporate operating experience.

NRC dealt with the problems posed by the calculational process at some length in its Appendix I opinion, admitted that present calculations are highly conservative, expressed support for realistic calculations, and provided several points for guidance "on how calculational procedures should be used in determining design objectives" to implement Appendix I. (Realistic models are preferred, an applicant may use approximations if his assumptions were conservative, parameters used should be best estimates, etc.)

The implications of this condition are numerous: (1) a margin of safety is presumably being provided the public because operating experience indicates that, for example, only 1 mR. of exposure to radioiodine occurs, despite NRC limitations of 15 mR.; (2) the utilities and ultimately the public are paying for "unnecessary" levels of control--in the sense that such control levels have been pushed beyond the balance point of ALARA analysis; (3) NRC regulations based on ALARA have a continuing credibility problem from a cost-benefit perspective; (4) NRC retains considerable discretion to allow facilities to operate above the "norm" at which they are demonstrably capable of operating, up to the higher NRC limitations--on a case-by-case basis; (5) NRC can authorize the cluster-siting of several reactors, with each meeting its Appendix I limitations, without breach of the 15 mR. limit for iodine. These unexpected benefits of lower exposure from actual operations are welcome, and demonstrate technological capabilities. They should be evaluated against the costs, and particularly against the condition that ALARA is not yet being fully-implemented and that the resulting decision-processes in NRC regulation remain considerably arbitrary. Since these unexpected benefits accrue at the discretion of the NRC and reflect current technological capabilities which are economically feasible for the utilities, it would appear that the responsible ALARA position for the NRC to adopt would be one of continuous self-limitation of its own discretion, through the continuous promulgation of rules reflecting these now achievable lower emission levels.

Appendix I, as the regulatory manifestation of ALARA, has additional implications for facility-siting and design standardization.

ALARA has not been invoked for purposes of siting new power facilities. This is due in part to the limited role played by the NRC in siting: a role basically of a "negative" review nature, prescribing geological, population and other constraints for facility-siting (70). NRC consideration of siting has, since 1970, been extended to the review of alternative sites available to a construction license applicant, under the requirements of the National Environmental Policy Act (NEPA) (71). This presumably ensures that the site to be selected is the most acceptable of those reasonably available, as determined by the traditional siting criteria employed by NRC. It does not ensure that the site will be optimal, from an ALARA perspective (72).

The primary siting role therefore has essentially fallen to the utility and the cognizant state energy boards recently established (49). This allocation of siting roles basically accords with the Constitution, which provides the states with land use authority under the general grant of "police power" (45), as discussed earlier. However, ALARA considerations could be translated into siting criteria by NRC and EPA, and offered to the states and utilities as guidelines for use along with other criteria used by the relevant state authorities. This task of working with the states to implement ALARA is discussed in Section C.3.

Standardization of reactor design remains an NRC objective to replace the practice of custom-designed reactors, in order to achieve cost reductions, quality control and enhanced safety (73). The standardization review process would test possible reactor design in different hypothetical sites--lake, river, offshore, etc.--with assumed population distributions. For a specific facility, site review would ideally be reduced to whether the actual site parameters are no worse than the hypothetical.

ALARA implementation can be in conflict with aspects of standardization, since the former calls for site-specific balancing of several factors to determine design limitations, and the latter provides for a generic approach to design limitations for plants which fall within certain site and population parameters.

Appendix I appears to integrate appropriately ALARA with standardization. The individual dose limits are already standardized--being derived from calculations involving hypothetical standard reactors and hypothetical standard sites (51). Case-by-case pressure on the population dose is provided by the requirement that all controls justified on a benefit-cost basis be added: if an actual site is worse than the standard site in some respects, radiation control measures will be added until the population dose is brought down to the benefit-cost value. Since the NRC is not directly involved in siting, there is still the possibility that an inferior site will be selected because of local or state land use decisions and utility acquisitions. However, the population would still be protected by the benefit-cost provisions, and the only undesirable effect would be an increase in electrical cost as compared with some other site. The state level is probably a preferable location for these tradeoffs to be made between dollars and land use objectives.

The NRC has recently run into difficulty in trying to achieve standardization without fully implementing the ALARA approach of Appendix I. In York Committee for a Safe Environment v. Nuclear Regulatory Commission (74), the Federal Court of Appeals for the District of Columbia determined that the NRC cannot consider the satisfaction of a single numerical guideline (the radioiodine--thyroid dose limit of 15 mR. per year) the equivalent of meeting its ALAP (now ALARA) regulations, since:

> The Commission definition...(of ALAP)...requires consideration of health and safety effects, costs, the state of technology, and utilization of atomic energy in the public interest. While the last two factors may be constant for any reactor built or operating during a particular time period, the first two will presumably vary depending on the circumstances of each reactor. Since two of the four factors which determine whether radioactive emissions are 'as low as practicable' are not constants, the Commission is precluded from determining that any particular positive level of emissions satisfies its requirement in all cases.

Since Appendix I, itself, specifies that in addition to satisfying the numerical guides,

> the applicant shall include in the radwaste system all items of reasonably demonstrated technology that when added to the system sequentially and in order of diminishing cost-benefit ratio effect reductions in dose to the population reasonably expected to be within 50 miles of the reactor...

the court concluded that "...(the) 'as low as practicable' standard requires individual consideration of the costs and benefits of reducing radioactive emissions from any particular reactor below the numerical guidelines." Therefore, the NRC is to be held accountable for the application of ALARA and benefit-cost on an individualized licensee basis, irrespective of the standarization measures it seeks to implement.

The implications of ALARA for NRC enforcement must also be addressed. Appendix I deals both with the design criteria and also with enforcement of operating conditions to meet these criteria, as noted earlier. The calculations involved can be broken down into two groups--those that deal with the amount of radioactivity that will be released, and those that predict how a given amount of radioactivity will spread through the environment, in particular into the food chain. For enforcement, actual emissions data are used in the second stage of the calculations (75).

The nuclear industry has made a case for the proposition that temporary violations of the standards must be tolerated, because (a) complex systems always vary in performance, (b) there is insufficient evidence that public health has been endangered, and (c) because it is highly important to maintain a continuous supply of electricity (76). Some participants in the Appendix I hearings argued that limitations established under Appendix I on a plant-specific basis should be treated as absolutes (77), and this argument appears to rest on distrust of administrative discretion in general, and of the NRC in particular. Certainly public confidence in the administrative process is a factor that cannot be ignored.

The NRC has chosen enforcement flexibility, providing "if the quantity of radioactive material actually released in effluents--during any calendar quarter is such that the resulting radiation exposure, calculated on the same basis as the respective design objective exposure, would exceed one-half the design objective annual exposure--the licensee shall: (1) Make an investigation to identify the causes for such release rates; (2) Define and initiate a program of corrective action; and (3) Report these actions to the Commission within 30 days from the end of the quarter during which the release occurred" (78).

Two features stand out, emphasizing the broad scope of NRC enforcement discretion:

(1) By implication, the licensee will be a [illegible] the emission standards by a substantial [illegible] nitely, without even calling the NRC's atten [illegible] the matter.

(2) If the licensee exceeds the exposure limit, and sets to work on a program of corrective action, there is no indication of the time-scale on which the licensee will be required to act.

Both these situations are governed at the discretion of the NRC.

The NRC may "require the licensee to take such action as the Commission deems appropriate" (79) and it would surely move against a licensee who proposed to continue indefinitely at a rate 1.9 times the Appendix I value; or who proposed to wait until his defective fuel rods reached the end of their normal life before replacing them. Nevertheless, a degree of trust in the NRC is called for, which may prove difficult to satisfy (80). Even though a complete specification of possible reactions to such developments is impossible, NRC could provide further details on enforcement, and specific criteria and time frames for corrective action (81).

Closely tied in with the enforcement issue is the previously-discussed matter of producing practicable standards. The fact that design calculations predict hypothetical exposures that are generally much higher than those observed in practice has a great deal to do with the flexibility afforded the NRC staff and with NRC tolerance of utility performace at variance with prescribed conditions. This tolerance is not shared by those who prefer regulation without discretion (without confidence in the NRC Staff), and who would be likely to seek to close down a plant because of temporary violations of limitations imposed on the basis of initial design calculations.

An NRC administrator is therefore in a dilemma--he must balance the known costs of reducing the operating level or of closing a power plant against the risks caused by indeterminate exposure of the public to new levels of radiation emission. Given that the initial design calculations are known to be highly conservative, an NRC official may decide to permit the situation to continue for some months; but, lacking data, is unable to present a rational defense of his action (82).

Finally, ALARA implies change with time. Thusfar, the NRC standards have been consistently tightened; but in principle, they can be loosened as well. It would therefore appear necessary to prevent any convenient loosening or maintenance of the status quo as a result of various pressures, particularly under less favorable economic circumstances for the power industry, by setting health boundary conditions as a necessary part of the ALARA quantification processes (83), as discussed in later sections of this chapter.

3. EPA and the States

EPA and the states have played insignificant roles in the regulation of radiation from nuclear power facilities; and there is no history of benefit-cost, ALARA and similar analytical techniques worth reviewing. Therefore, this section focuses largely on the implications of such analytical techniques for EPA and state decision-making, to the extent they enjoy discretion sufficient for implementation, as discussed above.

Although EPA has employed some form of balancing analysis in its regulatory efforts on radiation to date, the agency has not adopted the ALARA concept, nor articulated cost-benefit as its analytical method. In the agency's "Proposed Standards for Radiation Protection for Nuclear Power Operations" recently announced, the following language has been used to describe the analytical method employed:

> In developing the proposed standards, EPA has carefully considered, in addition to potential health effects, the available information on the effectiveness and costs of various means of reducing radioactive effluents, and therefore potential health effects, from fuel cycle operations. This consideration has included the findings of the AEC and the NRC with respect to practicability of effluent controls, as well as EPA's own continuing cognizance of the development, operating experience, and costs of control technology. Such an examination made it possible to propose the standards at levels consistent with the capabilities of control technology and at a cost judged by the Agency to be acceptable to society, as well as reasonable for the risk reduction achieved. Thus the standards generally represent the lowest radiation levels at which the Agency has determined that the costs of control are justified by the reduction in health risk. The Agency has selected the cost-effectiveness approach as that best designed to strike a balance between the need to reduce health risks to the general population and the need for nuclear power. Such a balance is necessary in part because there is no sure way to guarantee absolute protection of public health from the effects of a non-threshhold pollutant, such as radiation, other than by prohibiting outright any emissions. The Agency believes that such a course would not be in the best interests of society (84).

This preamble to the subsequently-announced limits on individual doses to members of the public and limits on quantities of certain long-lived radioactive materials in the general environment reflects a number of assumptions and exercises of EPA discretion that are not in harmony with the deployment of cost-benefit analysis and ALARA by NRC.

Sound regulation of radiation would require the EPA's exercise of its generally-applicable, environmental standard-setting functions be synchronized with the analytical processes of the NRC (benefit-cost, ALARA) and the other agencies such as the Department of Transportation (DOT) and the Food and Drug Administration (FDA), which EPA acknowledges as having "...the responsibility for the implementation and enforcement of both this guidance and these standards...as a part of their normal regulatory functions" (85).

The interrelationship of the regulatory functions of the several agencies is adequately demonstrated by the simple diagram presented as Figure 4.

Closely related to this issue is the need to adopt, at an interagency level, the same values for health effects, control costs and other elements of the common analytical processes to be used. EPA appears to be the most appropriate agency to assume the lead role in this task, as it is the only agency without obvious developmental interests in the construction and operation of the facilities emitting radiation.

The task of setting health parameters, or general societal levels of radiation in full recognition of risks and the lack of detailed knowledge of exposures and pathways, has been discussed in the prior section as a measure necessary for enlightening the public and preventing abuses which can creep into balancing analyses when they are used to achieve hidden objectives. This task should be carried out by EPA in conjunction with the Public Health Service (PHS) of the Department of Health, Education and Welfare (DHEW), as PHS is assumed to have such generally-applicable health guidance functions (86). To some extent, EPA undertakes this task in setting radiation standards for drinking water, under the provisions of the Safe Drinking Water Act (87), because such standards will have to be based on data and an overall record which emphasizes health considerations if they are to be upheld under judicial review since, in this case, health parameters for radiation exposures arising from ingestion of public water supplies would appear to be a necessary part of the record if the resulting standards are not to be considered "arbitrary and capricious" (88).

The EPA "proposed standards for environmental radiation protection from nuclear power operations" (89) contain a number of other issues which relate to the use of benefit-cost and ALARA-based analyses. Chief among these issues is EPA deferral of any controls on certain long-lived radioactive materials. EPA has previously acknowledged that "...no methods are available to effectively remove such materials from the environment once they have been released, and such releases thus imply irreversible commitments for exposure of future generations, except for natural occlusion in environmental sinks...it (is) especially important to consider the consequences of irreversible commitment of these discharges to the environment before they have occurred...Since control must be instituted long before the impacts associated with these releases occur, projection of anticipated health effects which could result from a release of these radionuclides constitutes a necessary basis for decisions concerning the

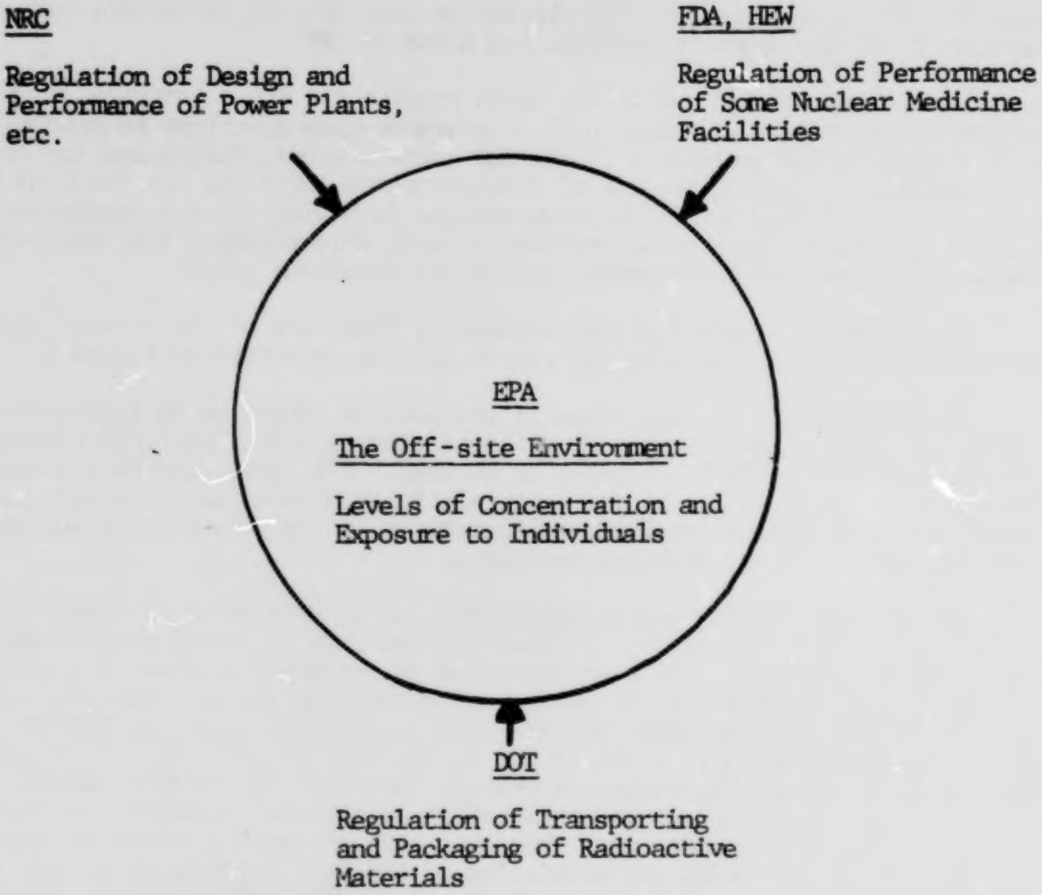

NRC
Regulation of Design and Performance of Power Plants, etc.
FDA, HEW
Regulation of Performance of Some Nuclear Medicine Facilities
EPA
The Off-site Environment
Levels of Concentration and Exposure to Individuals
DOT
Regulation of Transporting and Packaging of Radioactive Materials

FIGURE IV. 4: Regulatory Interrelationships need for institution of control over their release. Future decisions ought to consider these dose commitments with respect to both the types of development that should occur and the choice of controls that should be imposed... krypton and tritium are the radionuclides of major concern..." (90).

Despite this, EPA has, in the proposed standards, deferred controls on such releases. For example, controls on krypton-85 and iodine-129 have been deferred to an effective date of January 1, 1983, when successful demonstration of control technology may be achieved; controls on environmental release of tritium and carbon-14 have been deferred to such time as the knowledge base on control measures and their cost feasibility has been developed. "Tritium levels...are not expected to become significant until the late 1980's, and development programs are in existence for control... The Agency believes that the development and installation of controls...are important objectives, and will carefully follow the development of new knowledge concerning the impact and controllability of these radionuclides" (90).

Thus, a wide range of discretion is currently enjoyed by EPA to allow releases until feasible controls are available. Unless federal legislation requiring EPA to carry out affirmative duties in setting such radiation standards within the near future is enacted, EPA will not be accountable for such deferrals.

Another deficiency in the regulation of radiation, which has been discussed earlier, is the failure of any federal or state agency to translate radiation standards into enforceable siting regulations for nuclear power facilities. EPA has eschewed a siting role. As explained in the proposed standards: "....it (EPA) has not attempted to specify constraints on the selection of sites...even though the Agency recognizes that siting is an important factor which affects the potential health impact of most planned releases from operations in the fuel cycle. The (proposed environmental) standards were developed, however, on the assumption that sound siting practices will continue to be prompted as in the past and that facility planners will utilize remote sites with low population densities to the maximum extent feasible."

This assumption is, therefore, grounded in past practice, which fails to reveal a comprehensive siting approach on the part of the various siting decision-makers: the state and local authorities, the utility, and the NRC. Certainly, the states have only recently started to assume careful siting responsibilities through the creation of energy facility siting or review boards, thereby retrieving previously-delegated land use authority from local levels of government (91). But primary siting responsibility still resides with the local zoning and planning authorities in most states, and with the utilities and their siting practices and minimization of exposures and off-site levels have been apparently deficient in their decision-making (92). The siting guidances provided by the NRC do translate dose limits into site criteria, but have been inadequate to prevent siting in high population density areas, a problem which has been magnified by the NRC's ignoring of its own siting guidelines (93). At present, the public can only rely on litigation and judicial review to assure that siting is appropriately conducted. However, this path is costly and technically complex (94).

Further, a variety of procedural restrictions work against litigation and judicial review of agency decisions, as the method to ensure that the siting of specific facilities will be conducted in accordance with radiation limitations. For example, the courts have held that those who refrain from participation in rulemaking proceedings (e.g., the setting of ALARA limitations) may not obtain direct judicial review of the regulations resulting (95). This creates a situation which essentially precludes local or state interests from achieving judicial review of a facility-specific decision, when such review would call into question the appropriateness of generally-applicable regulations for the specific facility site in question. This serves to preclude most interest groups, since such groups generally develop or mobilize after a particular site has been chosen and evaluated, and therefore cannot be expected to have participated in earlier rule-making proceedings.

EPA, through its new Land Use office, could provide the required siting guidances based on those radiation levels and exposures which have been determined to be acceptable through the analytical procedures under discussion, thereby filling a gap in the present regulatory system as well as developing another facet of ALARA.

The limited authority of the states to regulate ionizing radiation and possible future roles involving state and local regulation of ambient water quality and land use, premised in part on reduction of radiation hazards, have been discussed. Although ALARA has not been considered in current uses of the police power, it could become a major feature of decision-making on siting by state and local authorities. EPA could develop and provide the states with the necessary siting guidelines, and further could authorize state compliance on ALARA siting through the state implementation plan requirements and other state program features of the Clean Air Act and the FWPCA (96). In this regard, EPA also has authority to regulate underground and public water supplies (84,87).

Federal preemption deserves careful analysis, despite the Northern States and Colorado PIRG decision of the Supreme Court, for as discussed in Section II, the doctrine is currently limited to authority for regulation of discharges; but the states possess general health and other ambient or offsite authority as a result of their police powers and the water quality provisions of FWPCA (but not the Clean Air Act). The extent to which such offsite authority can be used to force higher or more stringent discharge standards on a utility is still unresolved. It would appear that states could choose to set such ambient requirements, and thereby indicate a willingness to have their citizens bear higher costs for radiation control through the rate-setting structure, or even exclude nuclear power if necessary controls are not available, the national interest in nuclear power would not necessarily be harmed (97).

An assessment of the economic and operational implications for the future of nuclear power under such possible conditions is required to reach an appropriate decision on federal preemption vis-a-vis state authority over offsite effects. The issue is too technical to be resolved through future judicial decisions, but could be undertaken by a relatively disinterested assessor, such as the Congressional Office of Technology Assessment (OTA), which has necessary the institutional framework, methodologies and resources (98).

Consideration of enhancing the state role in this regard is justified because the values and weights used in analyses for regulating nuclear power are subjectively established. State and local values deserve consideration because of this condition of subjectivity which is inherent in decision-making on radiation, and because ultimately, the future of nuclear power will hinge on state acceptance, local values and the availability of facility sites--despite ALARA, benefit-cost, and federal preemption (99).

D. Basic Legal and Policy Considerations Attending Uses of Benefit-Cost Analysis

Balancing costs and benefits for decision-making has long been a practice of each of the three major institutions of the legal system--the legislature, courts and administrative agencies. The practice has been informal, implicit, and unsystematic, with little recognition of its inherent subjectivity, and with little concern for the limitations of the balancing techniques themselves.

However, several developments have now converged to make previous balancing practices in the administrative agencies unacceptable: (1) the passage of the National Environmental Policy Act and of other statutes for environmental protection whose provisions reflect Congressional understanding that agency regulation is a multiple-objective task which calls for a complete balancing of various interests (e.g., economic, environmental) except in cases of overriding threat to national security or public health; (2) the increasing sophistication of analytical techniques; (3) the opening up of agency rule-making and adjudicatory procedures to public scrutiny, and the growing desire of various societal sectors to use their increasing opportunities to influence the subjective features of such agency decision-making; (4) the increasing rigor of judicial review of agency decision-making, and the willingness of federal courts to examine more fully the procedural and substantive aspects of agency determinations.

In this section, an effort is made to identify some basic legal and policy problems with the use of benefit-cost to manage and control technical developments, and to develop some general principles to guide future uses of benefit-cost in government regulation. The judicial and administrative contexts in which balancing occurs are briefly examined in light of the discussion of preceding sections of this chapter, which focused on actual uses of benefit-cost to regulate ionizing radiation.

1. Common Law

Within the common law, tort law, which includes the fields of negligence and nuisance, has historically been of most significance for the securing of relief from the adverse health effects of technological activities. The essence of this field of law consists of judicial balancing. Green has summarized this feature of tort law as follows:

> The standard upon which the law of negligence is based is determined by weighing the magnitude of the risk of harm against the utility of the actor's conduct...the law of nuisance is based on

> the principle that conduct of the defendant is 'unreasonable in the light of its utility and the harm or risk which results'. As courts decide these cases, a body of laws comes into being that reflects a judgment as to the benefit-risk applicable to the activities in question. To the extent that decisions are made that risks outweigh benefits the activities may be enjoined by court action, or a rule of liability may be established that has the effect of increasing the costs incident to the activity and, in effect, deterring it (100).

Green has also described the limitations on the efficacy of the common law and its judicial applications in making benefit-risk determinations in the public interest:

> 1. ...the courts can act only on cases in which someone has been injured or clearly threatened...Accordingly, the system is not of much use in protecting society against very young...technologies.
> 2. Courts react only to information introduced in evidence in an adversary context, and judges and juries may not correctly understand technical issues. Common law principles, therefore, may sometimes not accord with scientific fact.
> 3. There are frequently immense difficulties, particularly where the risk is of a slow, creeping cumulative nature...in showing injury in a sufficiently legally adequate manner to warrant a favorable decision for the plaintiff.
> 4. Conversely, there are frequently immense difficulties in showing a causal relationship between an existing ill and the alleged technological source of the injury.
> 5. The common law is extended to new problems by a trial and error process in finding analogies to and distinctions from earlier precedents. The formulation of new common law principles that adequately reflect the benefits and risks of new technologies is, therefore, usually a long, slow and uncertain process (100).

This describes why the common law is of limited utility in controlling the adverse effects arising from activities using harmful substances such as radioactive materials. Further common law limitations arise from the inadequacy of the remedies available to the courts--compensatory damages and injunction. Damages are inadequate for the seriously-ill plaintiff, the malformed fetus, and their families. Damages are also inadequate for deterring or curbing the sources of the externality for broader societal protection purposes, since they may be awarded only to the few plaintiffs who have persisted in the courts for many years after the harmful activity was initiated. Therefore, the law has no significant or timely function of deterrence, of forcing more effective control measures when they are needed, on large scale technological activities such as nuclear power. Injunctive relief is rarely ordered by the courts against viable economic activities which are responsible for the harms, since such activities concurrently provide employment and a variety of other social and economic benefits which the courts are reluctant to curb, on the basis of their rough attempts at balancing (101).

For the case of nuclear power, with its releases of radioactivity and creation of long-term risks and harms, two further conditions limit use of the common law and its balancing processes for individual and societal protection: the effects of the presence of a large but not necessarily coherent government regulatory program on the common law, and the inability of the common law to evolve and meet new problems.

The existence of regulatory agencies and their control programs "...presents obstacles to the use of public nuisance actions where the existence of these agencies is used as a defense to injunction actions...even where statutory language has expressly preserved unimpaired common law remedies..." The obstacles include doctrines which enable the courts to defer consideration of the issues sought to be raised by a plaintiff, such as the doctrines of "primary jurisdiction" and "exhaustion of administrative remedies." The defense "that compliance with administrative orders or permits...render a nuisance action insupportable" presents another obstacle for the plaintiff to overcome. Thusfar, these defenses have met with little favor in the courts, but they indicate the possible synergistic relationship between common law and regulation (102).

The common law, despite its "creative continuity," is usually unprepared for some time to come to grips with new problems such as preconception injuries--genetic injuries of the types that can be caused by ionizing radiation. The reasons for this limitation range from the trivial to the substantial: from antiquated statutes of limitations which preclude legal action beyond relatively short time frames, to substantial difficulties of proving the causal relationship between injury and alleged harmful action, to judicial reluctance to recognize the very existence of a cause of action (103).

These, briefly described, are some of the major limitations on the common law and its uses of balancing techniques to provide for timely and effective social controls on a field such as nuclear power. Concurrently, and intimately associated with these limitations, the "market mechanisms" which have traditionally restrained new technologies until their externalities are reduced to socially acceptable levels do not work adequately for a field such as nuclear power which is marked by extensive government subsidization and protection (104).

2. Legislation and Government Regulation

Congress has, in light of these failings of traditional social controls, turned increasingly to the passage of legislation authorizing government regulation in accordance with highly-specific objectives, program designs and time frames. The burden borne by the regulatory agency becomes more socially significant as the adequacy of the common law and market mechanisms has diminished for particular fields of technology such as nuclear power.

Legislation and regulation applicable to nuclear power have been extensively discussed in the preceding chapter, and a variety of issues attending regulatory use of benefit-cost analysis--some structural, some substantive--have been addressed in the specific context of nuclear power. Therefore, this discussion will be limited to some of the fundamental issues that seem to attend use of benefit-cost analysis in government regulation, for the general case.

(1) The National Environmental Policy Act

The National Environmental Policy Act (NEPA), became applicable to federal agency decision-making in 1970 (105). NEPA contains the action-forcing provision (Section 102(2)(c)) which requires federal agencies to assess the environmental implications of their intended "major actions." These actions are those likely to have significant effects on environmental quality--such as the issuance of construction and operating permits for nuclear power plants (106), the promulgation of agency rules governing the performance of facilities and activities using radioactive materials (107), and the development of the breeder reactor program (108).

The structure of these assessments is specified in the Act, and the resulting environmental impact statements (EIS) must therefore discuss the range of anticipated environmental effects and alternatives to the proposed action, among other considerations (109). The assessment task must involve a "systematic, interdisciplinary approach" and must appropriately consider "presently unquantifiable environmental amenities and values" along with "economic and technical considerations" (110). Further, it is settled that the assessment must be used in agency decision-making, and that NEPA therefore requires "a rather finely turned 'and' systematic balancing analysis in each instance" (111).

Therefore, NEPA mandates the use of a balancing analysis in agency decision-making on all matters of environmental significance. However, whether the NEPA assessment process itself is to constitute the balancing analysis, or whether the NEPA assessment provides information which is to be ultimately balanced in some other agency's analysis along with other considerations, is presently unclear. Similarly, whether a formal benefit-cost analysis involving quantification of all factors, or an informal balancing on a best efforts basis is required, is unclear. Federal courts facing these issues in litigation challenging agency decision-making under NEPA have failed to resolve them conclusively and have occasionally stated that responsibility for evaluating uses of benefit-cost and determination as to its adequacy is a matter for Congressional review (112).

In light of these developments, agencies such as the NRC are now faced with a sequence of several balancing tasks, imposed as a result of both NEPA and the agency's own, self-imposed, requirements to use cost-benefit in its decision-making. For example, the following balancing analyses are all now potentially applicable to the NRC process of approving an application by a utility for a license to operate a nuclear power facility:

(a) Use of benefit-cost by the NRC in promulgating agency standards and other rules of general applicability to power plant performance;

(b) Use of benefit-cost by the NRC in promulgating limitations for a specific power plant;

(c) Use of balancing analyses in determining whether or not the separate construction and operating licenses should be issued for a specific plant.

For the first two steps, use of benefit-cost is mandated by Appendix I and other NRC regulations. Alternately, the use of a "balancing analysis" is mandated by NEPA when such steps apply to major actions of environmental significance.

For the dual licensing procedures of the third step, the NEPA mandate for "balancing analyses" is clear; and a federal court has recently cautioned that the NEPA requirement applicable to the issuance of an operating license may not be short-circuited--that a facility which meets NRC regulations does not concurrently and automatically qualify for licensing without the required weighing of risks and benefits under NEPA (113). Nevertheless, for the specific case before it, the court concluded that:

> Apart from the requirements of NEPA or similar ones already implicit under AEA (Atomic Energy Act), it would be pointless, and a waste of agency resources, to require the AEC to reapply efforts that have already gone into its basic health and safety regulations, in individual licensing proceeding, in the absence of some evidence that a particular facility presents risks outside the parameters of the original rule making. And in evaluating the sufficiency of agency determinations in particular cases it would be stultifying formalism to disregard the whole record and test AEC compliance by only the evidence received at so-called 'health and safety' hearings; or NEPA compliance only on the basis of so-called 'environmental' hearings.

This judicial decision promotes administrative efficiency by eschewing duplication of balancing analyses, and seems to make good sense. But it is clear that such efficiency is justified only when the risks and benefits appropriate for the facility-licensing balancing task under NEPA have been adequately considered in the prior balancing undertaken by the agency under its own regulations (e.g., Appendix I). Determination of these justifying circumstances is a complex task which rests ultimately with the courts. The extent to which the courts can handle this difficult task responsibly will therefore depend on judicial willingness to examine the substantive features of agency decision-processes, and the development of judicial expertise on cost-benefit (114).

(2) Confusion on Benefit-Cost Analysis

There is continuing confusion in regulatory agencies over the techniques of conventional benefit-cost and cost-effectiveness analyses, and this has implications for the integrity of the regulatory process.

> Benefit-cost analysis measures a planned program's costs against its expected benefits, using identical...units of measurement--most often dollars--on both sides of the ledger. ...Future benefits and costs are usually discounted at some rate to reduce them to present values (117).

The balance point at the margin between benefits and costs is the point at which a program decision or a standard is "justified."

> Cost-effectiveness analysis compares the cost of alternative means for effectively achieving an agreed upon goal. The means may be programs, technologies, devices or combinations of approaches. The goals are often expressed in terms of public policy as laws and standards (118).

The ALARA concept and NRC regulations discussed earlier are expressed in terms of conventional benefit-cost, as a regulatory search for balance points at which control levels can be prescribed. This implies that there are no overall primary goals which have been agreed upon--no overall health goals or health parameters, for example--and that regulation is a dynamic and iterative process which evolves as inputs to the process change over time. Thus, the benefit-cost approach essentially excludes the adoption of fixed objectives for life and health, and its NRC application to radiation regulation fully reflects this.

However, EPA expresses its approach to setting general environmental standards for radiation exposure and levels as being a "cost-effectiveness" approach (119). Presumably, therefore, objectives have been chosen or adopted by EPA for which alternative control approaches have been compared. Since EPA has not yet expressed any choice of health objectives or parameters and since EPA consistently discusses its regulatory approach as being fully compatible with feasible control measures as determined by NRC, it may be that the EPA cost-effectiveness approach to setting radiation standards has been conducted to achieve the technical-economic feasibility parameters designated by NRC.

Of course, the foregoing analysis can be criticized on the basis that the NRC has been conducting its benefit-cost analyses within the context of assumed upper limits for human exposure and environmental levels of radiation, upper limits (such as the 500 mR. standard) defined by various expert groups such as ICRP and NCRP. These advisory organizations are basically self-governing and unaccountable, and NRC may adopt their recommendations only as they can conveniently be implemented by the present state of the art of control technology. Therefore, without the setting of health parameters and upper environmental levels by an agency such as EPA in an open, accountable process as discussed in preceding sections of this chapter, benefit-cost and cost-effectiveness analyses used by NRC and EPA may lack credibility in the societal context.

(3) Valuation in Cost-Benefit Analysis

Cost-benefit inevitably requires a series of analytical steps--

(a) identification of effects (costs, benefits)

(b) determination of their magnitude

(c) estimation of their probability of occurrence

(d) determination of the significance of each effect (its value, in numbers)

(e) a summing up and determination of the resulting ratio.

Although one may quibble about an agency's conduct of the first three steps, these are relatively open to professional critique and lay opinion, and differences in judgement can be resolved. The fourth step--determination of the significance of each effect--remains a troublesome issue. How to value deaths and illnesses and dislocations of various types, for this generation and for future generations?

The public at large must be invited into this quantification task. But how? And how to guarantee an appropriate distribution of effects and the protection of minority rights (e.g., most exposed individuals offsite). And how to guarantee the rights of unrepresented (future generation), particularly in light of inadequate societal values placed on long-term, intangible effects? No structure or concepts presently exist to resolve these valuation issues attending the use of benefit-cost analysis (or for that matter, cost-effectiveness analysis), beyond the techniques for eliciting societal preferences which have recently evolved in the applied social sciences.

Congressional rejection of benefit-cost for setting standards and for other features of regulatory decision-making, in favor of the determination of health parameters and other ambient effect-oriented approaches, is found both in legislation relating to determination of highway and vehicle safety standards, and in the legislative history and enactments on Clean Air and Water Pollution Control (See Section C.3.) The federal courts, in reviewing regulatory agency decisions on pollutants with considerable health implications, have also demanded that health factors be given a high priority in the thinking and nature of such decisions, implying that benefit-cost alone would be insufficient (115).

(4) Technical and Economic Information in Beneift-Cost Analysis

In conducting benefit-cost analyses for developing standards, issuing permits, prescribing design specifications and operating procedures, and other aspects of regulation, information on the state of the art of various control technologies and skills is critical. The information essentially relates to the reliability of various control techniques, commercial availability, and costs. Where the control techniques under consideration have already been practiced or used in other sectors of industry or other nations, or where the control is available on a fixed-price basis or is otherwise a production-line item, the information on reliability, availability and costs is fully known to government regulators, and should be relatively accurate.

However, where the control techniques under consideration are untested or in a developmental or prototype or experimental stage, or where the technique will have to be "hand-tooled" or otherwise applied on an ad hoc basis to specifications furnished by the potential purchaser, information on reliability, availability and costs is normally not known to government regulators except as submitted by the regulated industry. Securing accurate information under these circumstances can be difficult, depending on the industry in question and applicable legislation and regulations enabling agency access to industrial information.

The quality of information from industry under these latter circumstances has been openly criticized in Congress and the agencies for some time. Such Congressional skepticism led to the passage of the Clean Air Act, with its mandate for relative disregard of technical feasibility in establishing health-related air quality regulations (116).

The nuclear power industry is the primary source of information on the technical and cost features of proposed radiation control developments, and such information following NRC evaluation, is used in NRC benefit-cost analyses for setting regulations. Ongoing review of the quality of industrial information, and of the quality of an agency's evaluations and uses of such information, would seem necessary to ensure that benefit-cost will not be abused--in light of regulatory experience with other industrial sectors.

(5) Forcing Advances in Control Techniques

Closely related to the foregoing issue of information quality control is a larger question of critical importance to the regulation of health hazards on a benefit-cost and iterative basis: is the regulatory program appropriately forcing advances in control techniques and their timely use on the regulated? This is a question that should be addressed at the time of design of legislation at the Congressional level, and also continuously throughout the development of regulations and their enforcement at the agency level.

This question can best be answered, for the nuclear power case, by an extensive, independent assessment of NRC regulations and their effects in forcing the development and use of new radiation control techniques by industry and government itself.

However, some general impressions as to the implications of benefit-cost regulation for technology-forcing can be offered.

First, because of the difficult information problem described earlier, analyses may employ misleading information and therefore not force advances in techniques which are otherwise imminent or reasonable to expect.

Second, the benefit-cost task of balancing contains no inherent incentive for the development of control techniques, since it uses information on available and proven techniques and tends, in this regard, towards maintenance of the status quo on technological matters.

Unless health objectives or parameters are agreed on and employed, the health effects can be conveniently selected and valued at levels which, in the analysis, will bring about a balance point always within the realm of currently feasible techniques. In this sense, those health effects which, if valued, would bring about a new technique-forcing result, which could have significant economic impact on plants, can be excluded from the analysis on various grounds. For example, the long-term global health effects of iodine, krypton, and carbon-14 release (48), if valued (and the valuation would certainly and always be arbitrary) could have a significant impact on the economics of nuclear power until new and economic techniques became available to lessen or prohibit their discharge.

For this reason, benefit-cost as a basis for regulating pollutant discharges can be regarded as a mandate for lessening discharges and ambient effects only as new techniques become feasible. By not forcing and directing advances in control techniques by means of the threat of shutdown if health parameters are not achieved, benefit-cost can become a mechanism for "economically convenient" regulation.

(6) Some Troublesome Assumptions in Benefit-Cost Analysis

Underlying the application of benefit-cost analysis to ionizing radiation are two assumptions:

The first assumption can be described as confidence in management capability and technological advances to handle future problems which have been predicted on the basis of current practices. Presently allowed levels for the production of radioactive wastes and for the operational release of radioactive iodine, krypton and tritium, for example, are justified on the assumption that when these substances closely approach dangerous environmental levels, management capabilities and new techniques will be available and feasible to prevent the levels from actually being reached. In light of the irreversible and dangerous nature of such levels for many generations, this assumption is a critical one and must be well-founded. The basis for this assumption about future capabilities to solve the radioactive waste material and carbon-14 problems now building up, should be examined in open forum for societal decision- or policy-making beyond the NRC and EPA levels.

The second assumption relates to the presumed mutability of societal values. Measuring benefits is based on a snapshot of current values and consumption patterns, tends to assume their perpetuation, and uses these values for determining the benefits in the analysis. This leads inevitably to future projections based on these present values, inadequate consideration of alternatives such as "social engineering" or consumer education, and has obvious consequences for the benefit-cost analyses in question.

E. Conclusions

This review of benefit-cost has been limited to its use in regulatory context--the context of administrative and judicial decision-making on the control of the harmful externalities of various regulated activities such as energy production.

The questions about uses of benefit-cost in the regulatory context which have been raised in this chapter are significant in that they relate to societal capacity to protect human health and welfare for this and the succeeding generations which will bear the risks of contemporary decisions on radioactivity and other harmful substances.

Serious consideration should be given to the adoption of alternatives to traditional economic benefit-cost analysis for such regulatory decision-making, in the light of the questions which have been raised. It is unlikely and unacceptable that alternatives will be chosen which do not balance various factors in some systematic and structured process. For example, one possible alternative is an appropriately comprehensive cost-effectiveness analysis for societal health objectives and risk parameters (e.g., carcinogenic risks) established by Congressional or other institutional processes which are acceptable as being socially representative. Cost-effectiveness analysis requires the articulation of objectives, the weighing of the alternative means to achieve these objectives, and the selection of the least costly approach.

The task of making such decisions by Congress or other acceptable institutions on health objectives would certainly be difficult, but once accomplished, the results could serve to ensure that regulatory decision-making on energy and other activities involving harmful externalities is accountable to articulated societal objectives for environmental health. This process would additionally force consideration of our role in providing stewardship for future generations.

FOOTNOTES

1. See generally, statutes cited in "Radiation Initiatives," memorandum of Office of Radiation Programs, U.S. Environmental Protection Agency (June 1975). The most important statutes are discussed in this chapter with specific citations.

2. 42 USC 2233. "Each license shall be in such form and contain such terms and conditions as the Commission may, by rule or regulation prescribe to effectuate the provisions of this chapter."

3. Executive Order 10831 (14 August 1959), Section 274h of the Atomic Energy Act of 1954, as amended by Public Law 86-373 (23 September 1959).

4. 42 USC 2233 (see footnote 1). The statute makes no reference to external advice.

5. 10 CFR 20 in general, and 10 CFR 20.105 for offsite individual exposures.

   "There may be included in any application for a license or for amendment of a license proposed limits upon levels of radiation in unrestricted areas--The Commission will approve the proposed limits if the applicant demonstrates that the proposed limits are not likely to cause any individual to receive a dose to the whole body in any period of one calendar year in excess of 0.5 rem." (Note: by implication, exposures in excess of 0.5 rem may be approved.)

   Although the regulations permit exposures of 500 mR. it has been found that actual exposures have been less than 1 mR. for nearly all plants.

6. Energy Reorganization Act of 1974, Section 201(f), 88 Stat. 1243.

7. Reorganization Plan No. 3 (1970) Section 2(a)(5 USCA Appendix II).

   "There are hereby transferred to the Administrator (of the EPA): all functions of the Federal Radiation Council (42 USC 2021(h)).

8. 10 CFR 20.1(c)

   The NRC stated that no change in substance was intended, but the change was intended to clarify the purpose of dose limitation. The change brought the NRC into agreement with the International Commission on Radiological Protection, which had previously made the same change. (Publication 22: Implications of Commission Recommendations that Doses be Kept as Low as Readily Achievable), International Commission on Radiation (1973).

9. Proposed *Appendix I* was published in the Federal Register June 9, 1971 (36 F.R. 11113). Public hearings commenced January 20, 1972. The Nuclear Regulatory Commission issued its opinion and final version on April 30, 1975, announced in the *Federal Register* on May 5, 1975.

10. Nuclear Regulatory Commission: *Rulemaking Hearing on: Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low As Practicable" for Radioactive Material in Light-Water Cooled Nuclear Power Reactors Effluents*, Docket No. RM-50-2 (April 30, 1975). (Hereafter referred to as the NRC opinion.)

11. NRC opinion, p. 2; also p. 4. "It should be emphasized that the Appendix I guides as here adopted by the Commission are not radiation protection standards. The numerical guides of *Appendix I* which we announce today are a quantitative expression of the meaning of the requirement that radioactive material in effluents released to unrestricted areas from light-water cooled nuclear power reactors be kept 'as low as practicable'."

12. Various *Regulatory Guides* are now being promulgated to govern power plant siting, design and performance, and are built upon *Appendix I*, making it even more a practical matter that *Appendix I* serves as a regulation. See for example; U.S. NRC Regulatory Guides 1.109, 1.110 and 1.111 (March 1976).

13. See Note 7, supra.

14. Environmental Protection Agency, "Proposed Standards: Radiation Protection for Nuclear Power Operations: 40 FR. 23420 (May 29, 1975); and Draft Environmental Statement. (Uranium Fuel Cycle). Various positions have been taken on the proposed standards. See for example: Statement of Roger Mattson, Director, Division of Siting, Health and Safeguards Standards, NRC (March 8, 1976); Comments of the Natural Resources Defense Council (Sept. 15, 1975).

15. Reorganization Plan No. 3, 1970, Note 13, supra.

> "...Our National government today is not structured to make a coordinated attack on the pollutants which debase the air we breathe, the water we drink, and the land that grows our food. Indeed the present governmental structure for dealing with environmental pollution often defies effective and concerted action...
>
> Despite its complexity, for pollution control purposes the environment must be presented as a single, interrelated system. Present assignments of departmental responsibilities do not reflect this interrelatedness. ...
>
> In organizational terms, this requires pulling together into one agency a variety of research, monitoring, standard-setting and enforcement activities now scattered through several departments and agencies.

As no disjointed array of separate programs can, the EPA would be able--in concert with the States--to set and enforce standards for air and water quality and for individual pollutants. This consolidation of pollution control authorities would help assure that we do not create new environmental problems in the process of controlling existing ones. Industries seeking to minimize the adverse impact of their activities on the environment would be assured of consistent standards covering the full range of waste disposal problems."

16. Clean Air Act, 42 USC Section 1857c et seq.

17. Federal Water Pollution Control Act Amendments of 1972, 33 USC Section 1251 et seq.

18. FWPCA, Title II, 33 USC Section 1251 et seq., CAA, 42 USC Section 1857c et seq.

19. See 42 USC Section 1857c-7 and 33 USC Section 1317, sections from the air and water pollution acts, respectively.

20. EPA has articulated an important concept for radiation regulation, the "radiation dose commitment" concept, which "... simply defined, is the sum of all doses to individuals over the entire time period the (radioactive) material persists in the environment in a state available for interaction with humans...calculated for a specific release at a specific time...obtained by summing the person-rems delivered in each of the years following release to the environment until the material has been reduced to innocuous levels by either radioactive decay or removal from the biosphere by other means." The concept is an important one, which has yet to be accepted or even publicly acknowledged by source control authorities. As EPA has noted: "Since control must be instituted long before the impacts associated with these releases occur, projection of anticipated potential health effects which could result from the release of these radionucleides constitutes a necessary basis for decisions concerning the need for institution of control over their release. Future decisions ought to consider these dose commitments with respect to both the types of development that should occur and the choice of controls that should be imposed." (From Environmental Radiation Dose Commitment: An Application to the Nuclear Power Industry, U.S. E.P.A. Office of Radiation Programs, EPA-520/4-73-002, Feb. 1974, pp. 3, 5.)

21. Memorandum of Understanding Between EPA and AEC, 38 F.R. 24936 (Sept. 11, 1973) par. (1); and 38 F.R. 32965 (Nov. 29, 1973). See also Colorado PIRG case, Note 47, infra.

22. Executive Order 10831 (14 August 1959); Section 274h of the Atomic Energy Act of 1954, as amended by Public Law 86-373 (23 Sept. 1959). Presently found at 42 U.S.C. 2021(h).

The Federal Radiation Council (FRC) was established by executive order in 1959.

In the accompanying press release from the White House it was noted that:

"(d) The Department of Health, Education, and Welfare (will) continue as the Federal focal point for guidance and assistance to the states with respect to contamination by and biological effects from radiation sources not now under control of the Commission (AEC)."

It is thus apparent that the FRC was created to advise regulatory agencies, but that no standard setting authority was given or intended.

23. 42 USC 2012(e).

24. National Environmental Policy Act of 1969, 42 USC Section 4321 et seq (1970): Section 102(2)(C) requires that the agency preparing an Environmental Impact Statement (EIS) "shall consult with and obtain the comments of any Federal Agency which has jurisdiction by law or special expertise with respect to any environmental impact involved."

25. "Guidelines: Preparation of Environmental Impact Statements", U.S. Council on Environmental Quality, 38 F.R. 20550 (August 1, 1973).

26. The Clean Air Act, 42 USC 1857h-7 (1970), Section 309.

27. Clean Air Act, 42 USC 1857c-7 (1970).

28. FWPCA, 33 USC Section 1362 (1972).

29. SDWA, 42 USC Section 300f(6)(1974).

30. SDWA, 42 USC Section 300f-j (1974).

31. Clean Air Act, 42 USC Section 1857c-7 (1970).

32. FWPCA, 33 USC Section 1362 (1972).

33. FWPCA, 33 USC Section 1317 (1972).

34. FWPCA, 33 USC Section 1342(b)(1972).

35. Colorado PIRG v. Train, FSupp 991 (1974); 507 F.2d 743.

36. Train v. Colorado PIRG, _____ U.S. _____, 8 ERC 2057 (June 1, 1976).

37. 42 USC Sections 2131-2140; 10 CFR 20.

38. 40 CFR Section 125.1(x)(1973); COMMENT.

39. FWPCA, 33 USC Section 1316 (1972).

40. FWPCA, 33 USC Section 1362 (1972).

41. FWPCA, 33 USC Section 1362(6)(1972).

42. FWPCA, 33 USC Section 1317 (1972).

43. Clean Air Act, 42 USC Section 1857c-5. The states were to adopt plans to enforce the EPA's national primary and secondary air standards; subject to the Administrator's approval. The EPA has had to take over enforcement of several state plans.

    FWPCA, 42 USC Section 1311-1345. The states are to set set water quality standards and to implement them, subject to EPA approval. State-EPA interaction is complex. The states may set stringent standards and thereby impose more stringent conditions upon individual polluters than the EPA national effluent limitations require.

    SDWA, 42 USC Section 300g-2, provides that the states are to have primary enforcement responsibility under the Act. The state must adopt regulations at least as stringent as the EPA's national primary and secondary water quality standards, and must also provide for enforcement procedures that meet with the Administrator's approval. See "Interim Primary Drinking Water Regulations: Notice of Proposed Maximum Contaminant Levels for Radioactivity", 40 F.R. 34324 (Aug. 14, 1975), 40 CFR Section 141.

44. 447 F 2d 1143 (1971); aff'd. 405 U.S. 1035 (1972).

45. U.S. Const. Amend. 10. "Public safety, public health, morality, peace and quiet and law and order do not constitute the entire scope of the police power." Berman v. Parker, App. D.C. 1954, 75 S.Ct. 98, 348 U.S. 26.

46. See Protection Against Ionizing Radiations: A Survey of Current World Legislation, World Health Organization, Geneva (1972); in particular, the section on "State Legislation" in the United States, pp. 277-283.

47. See Water Quality Standards Criteria Digest: A Compilation of Federal/State Criteria on Radiation, U.S. Environmental Protection Agency (August 1972).

48. In Northern States, the State of Minnesota attempted to regulate the discharge of radioactive effluents from a power plant, using standards that were considerably more stringent than those of the AEC. The Circuit Court held that preemption of such regulation was implicit in the Atomic Energy Act of 1954; and the Supreme Court approved without comment.

49. M. Baram, "State Energy Legislation and the Siting of Facilities" in The Northeastern States Confront the Energy Crises, Conference Proceedings, N.Y. State Senate (1975), NSF-RA-G-75-050.

50. "Health Education and Welfare: Suggested State Regulations for Control of Radiation", 40 F.R. 29749 (15 July 1975).

51. See *Policy Statement: Relationship Between Radiation Dose and Effect*, EPA *(3 March 1975) for EPA adoption.* For background on AEC and FRC positions, see *Concluding Statement of Position of Regulatory Staff: Public Rulemaking Hearing on Numerical Guidelines for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low As Practicable" for Radioactive Material in Light-Water-Cooled Nuclear Power Reactors*; Docket No. RM-50-2, U.S. Atomic Energy Commission (February 20, 1974), pp. 36 and 37.

52. Note 10, See pp. 66, etc. "Consolidated National Intervenors argued that no radioactive discharges should be permitted." (p. 66)

53. Note 10, See p. 106: "In our judgment the guidelines we have adopted are necessary and reasonable", (re NRC final decision on employment of Appendix I, in reference to opposing views).

54. Note 10, See various NRC statements, expressing adoption of the cost-benefit approach--e.g., p. 11, 12, etc.

55. 40 F.R. 33029. See Note 15, supra.

56. See for example: *Crowther v. Seaborg*, 312 F.Supp. 1205 (D. Colo. 1970), (challenging 10 CFR 20, in part); *Calvert Cliffs Coordinating Committee v. AEC*, 441 F.2d 1109 (D.C. Cir. 1971), (challenging AEC re non-compliance with NEPA).

57. 35 F.R. 18385 et seq. (December 3, 1970).

58. Note 10, See pages 2-4.

59. Note 51, supra. See *Concluding Statement*..., pages 41-43.

60. Note 51, supra. See *Concluding Statement*..., pages 14-15.

61. Note 10, See pages 12-16.

62. Note 10, See p. 11.

63. Note 10, See pages 91-95.

64. Note 10, Page 90.

65. Note 10, Page 11.

66. Note 10, Pages 113-119.

67. Note 10, Page 35.

68. Note 10, Pages 31, 34-35, etc. Also see *General Design Criterion 64*, "Monitoring Radioactivity Releases" of *Appendix A* to 10 CFR Part 50; and *Regulatory Guide 4.1* etc. of the AEC.

69. Note 10, Pages 126-130. See also page 33. The critical iodine-milk path can be tested. See AEC *Regulatory Guide 4.3*.

70. 10 CFR Section 100.

71. NEPA, 42 USC Section 4321 et seq. (1970).

72. The *Calvert Cliffs* decision (Note 70, supra) calls for AEC use of the full environmental impact statement in facility decision-making, and for such decision-making to be founded on a "finely-tuned, balanced analysis." This clearly does not require selection of the optimal site on the basis of ALARA criteria and conditions.

73. See Sections 29 and 182b of 42 USC 2039, 2232b, the Atomic Energy Act; and proceedings of the ACRS Subcommittee on Standardized Nuclear Unit Power System (SNUPPS). Also see *Policy Statement on Standardization of Nuclear Power Plants*, AEC (April 28, 1972); *State on Methods for Achieving Standardization of Nuclear Power Plants*, AEC (March 5, 1973).

74. 6 ELR 20107 (D.C. Cir. Dec. 9, 1975).

75. Note 10, Pages 33, 34, etc.

76. Note 10, Pages 17-19, etc.

77. Note 10, Page 105.

78. Note 10, Page 105.

79. 10 CFR 50.36(a)(2).

80. Difficulties in the operation of Vermont Yankee and other facilities, resulting in releases above prescribed levels, have aroused public interest groups and local and state health authorities, particularly in light of the failure of the AEC to respond with timely enforcement.

81. See "Criteria for Determining Enforcement Action and Categories of Non-Compliance", and other elements of 10 CFR Part 2, for specifications on enforcement to date. Also see *Report to the Congress on Abnormal Occurrences: Jan.-June 1975*, U.S. NRC, P.B. 245-404 (Oct. 1975) which provides interim criteria for abnormal occurrence determination. Of particular interest is that offsite receptor exposure does not qualify as an abnormal event unless it is in excess of 500 mR., far in excess of limitations now imposed under ALAP, and indicative once again that despite technological advances over a decade, 500 mR. remains as the only enforcable limitation of the NRC.

82. The courts have been sympathetic to delay, when "further study" by the NRC is undertaken. See Nader v. NRC, 5 ELR 20342 (D.C. Cir. May 30, 1975) for judicial tolerance of NRC delay in the matter of emergency core cooling systems.

83. Note 14, supra. The EPA's proposed environmental standards for the uranium fuel cycle (annual dose equivalents to the whole body, thyroid, etc.) were developed on the basis of considering health effects and the costs of available control measures. The proposed standards reflect a balancing, and do not constitute the health boundary conditions discussed.

84. Proposed Standards: Radiation Protection for Nuclear Power Operations, EPA, 40 F.R. 23420 (May 29, 1975).

85. Id. Page 2340.

86. Public Health Service Act, 42 USC 241 and 243.

87. 42 USC Section 300f-j. See EPA "Interim Primary Drinking Water Regulations: Proposed Maximum Contaminant Levels for Radioactivity," 40 F.R. 34324 (Aug. 14, 1975).

88. Administrative Procedure Act, Section 10(e)(B)(1), 5 USC Section 706 (2)(A)(1970).

89. *Environmental Radiation Dose Commitment: An Application To The Nuclear Power Industry*, EPA (February 1974).

90. Note 84, Pages 23422-23423.

91. See state enabling acts for New York, Maine, Massachusetts, cited in Baram, note 61, supra; and implementing regulations.

92. 10 CFR Section 100.

93. *Porter County Chapter of the Izaak Walton League of America v. AEC*, 5 ELR 20274 (7th Cir. April 1, 1975); reversed U.S.S. Ct., 6 ELR 20040 (Nov. 11, 1975). However, NRC siting criteria have forced several proposed sites to be abandoned.

94. *Alyeska Pipeline Service Co. v. Wilderness Society*, 5 ELR 20286 (U.S. May 12, 1975).

95. *Gage v. AEC*, 156 U.S. App. D.C. 231, 479 F.2d 1214 (1973).

96. CAA, 42 USC Section 1857c-5; FWPCA, 33 USC Section 1313.

97. See H.R. 441, a bill introduced in the 1st session of the 94th Congress by Congressman Fish (January 14, 1975), which would allow the states to regulate the emission of radioactive effluents concurrently with the NRC.

> "(3) it is the intent of this Act to establish the concurrent authority of the several States to regulate such radioactive emissions, including the authority to enforce standards for such radioactive emissions, which permit lesser quantities of such emissions from such facilities than do the standards established by the Commission."

98. 2 USC Section 475.

99. For judicial recognition of the role that local values and laws should play in federal agency decision-making (in the NEPA context), see Maryland Planning Service v. U.S. Postal Services, 5 ERC 1725 (1973).

100. H. Green, "Comments on Legal Mechanisms", in Perspective on Benefit-Risk Decision-Making, National Academy of Engineering (1972).

101. See M. Katz, "The Function of Tort Liability in Technology Assessment", 38 Univ. Cincinnati L. Rev. 587 (1969) and cases cited therein.

102. Quotes from 60 ALR 3d 665.

103. See C. Moore, "Radiation and Preconception Injuries: Some Interesting Problems in Tort Law", 28 S.W.L.J. 414 (1974).

104. See discussion of the Price-Anderson Act, 42 U.S.C. Section 2210 et. seq. in "Atomic Power and Indemnification of Accident Victims," p. 17-35, in A. Reitze, Environmental Planning: Law of Land and Resources, N. American Int'l Publ. (1974).

105. 42 USCA 4321 et seq. (1970).

106. 10 CFR Part 51, for NRC's "Licensing and Regulatory Policy and Procedures for Environmental Protection."

107. See, for example, 39 FR 5356 (Feb. 12, 1974) for NRC notice of preparation of environmental impact statement on the "Wide-Scale Use of Mixed Oxide Fuel" (Plutonium Fuel Cycle).

108. Scientist's Institute for Public Information v. AEC, 5 ERC 1418 (D.C. Cir. 1973).

109. 42 USCA 4332(2)(C).

110. 42 USCA 4332(2)(A) and (B).

111. Calvert Cliffs Coordinating Committee v. AEC, 2 ERC 1779 (D.C. Cir. 1971).

112. M. Triantafillou, "Cost-Benefit Analysis in the Context of NEPA," unpublished paper (Dec. 1975), Harvard School of Design.

113. Citizens for Safe Power v. Nuclear Regulatory Commission, 6 ELR 20095 (D.C. Cir. Dec. 22, 1975).

114. See H. Leventhal, "Environmental Decision-Making and the Role of the Courts," 122 U. Pa. L. Rev. 509 (January 1975) for an extremely useful analysis of judicial review and its limitations.

115. See EDF v. Ruckleshaus, 439 F. 2d 584 (D.C. Cir. 1971); EDF v. EPA, 465 F. 2d 528 (D.C. Cir. 1972).

116. J. Bonine, "The Evolution of Technology--Forcing in the Clean Air Act," Monograph 21, Environment Reporter, Bureau of National Affairs, v. 6, n. 13 (July 25, 1975).

117. FWPCA, 33 USC Section 1314(b)(1)(B).

118. FWPCA, 33 USC Section 1314(b)(2)(B).

119. FWPCA, 33 USC Section 1316(a); 10 CFR 40.

CHAPTER V

BENEFIT-COST ANALYSIS FOR ENERGY PRODUCTION

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CHAPTER V

BENEFIT-COST ANALYSIS FOR ENERGY PRODUCTION

A. Introduction

Chapter III sets forth the concepts involved in benefit-cost analysis in the abstract and defines the terms employed, again in the abstract. This chapter examines its application to the use of nuclear energy in the generation of electric power. The question to be addressed is whether benefit-cost analysis can be used in the development of a national strategy for energy production.[1]

It may be argued that, in addition to the choice between nuclear and conventional technology, there is also another choice--that of supplying the power or not supplying it. Although the provision of new generating capacity to some extent involves the replacement of obsolescent capacity, the bulk of the requirements for new capacity are to satisfy expected growth in electricity consumption. If that growth were to be reduced or eliminated, the need for new capacity would be correspondingly reduced.

Conservation[2] can take place in response to three different motivations. The first is the economic motivation, or response to price. As previously noted, when external environmental costs become internalized--that is, as costs which were not previously components of price become components through the installation of cooling towers, the use of low-sulfur fuels, the treatment of stack gases, etc.--the price of electricity may be expected to rise. Consumers, both individual and business, can then be expected to use less electricity.

Conservation also occurs as a result of what may be termed individual ethical motivation. For some it is both a moral obligation and a source of personal satisfaction to reduce their electricity consumption, even if this entails some loss of material well-being (e.g., doing without air conditioning and tolerating lower indoor temperatures in winter). Or, as was true during the oil embargo of 1974, individuals and businesses may practice conservation as a matter of patriotism, to do their part during a period of national emergency.

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[1] There are, of course, other energy sources and technologies that could be considered and encouraged as alternatives. At this point, however, these sources, such as solar, geothermal, wind, tidal, etc., are potential as contributors to the national energy picture. For the purposes of this report, it is preferable to investigate the application of benefit-cost analysis to existing technologies.

[2] Unless otherwise noted, the word conservation is used to mean conservation of electricity.

Thirdly, conservation may occur as a result of legislation or regulation which decrees that less be used.

Conservation under the first two motivations can be said to dispose of the issue. To the extent consumers respond to higher prices by using less electricity and to the extent they conserve for personal ethical reasons, conservation is "automatic." It does not depend on a decision reached through the kind of formal benefit-cost analysis being applied here. With respect to conservation through governmental action, the cost-benefit comparison that is relevant is a matching of the costs and benefits of having the additional power against the costs and benefits of doing without it, including the costs of governmental action referred to above. We will here consider only the choice between the use of nuclear versus fossil fuel technology.

B. Concepts and Philosophy

The problem of determining the most beneficial means of providing adequate future electricity supply is complicated by the large number of alternatives. The judgment we have made that the proper comparison is between nuclear and fossil fuel technology does not mean that we have, therefore, two neat packages, labeled "nuclear" and "fossil fuel." Within the former there are the choices among light-water reactors, high temperature gas reactors, liquid metal fast breader reactors, and so forth. Within the latter there are the choices among coal, oil and gas as the fuel and the technologies for the use of each.

In view of the large number of alternatives possible, a strategy of benefit-cost analysis is required which will permit the breakdown of costs into manageable portions. The costs must be integrated over time, since some are of long duration, many times greater than a single lifetime (e.g., the disposal of long-lived nuclides, the somatic and genetic effects to present and future generations from exposure of individuals to mutagenic and carcinogenic substances from burnt fuel or to radiation, the exhaustion of a given resource, etc.), or are likely to occur only rarely (e.g., catastrophic failure, sabotage).

To be of maximum usefulness in decision-making, the benefit-cost analysis should be part of any over-all analytical sequence something like the following:

1. Identify as many as possible of the costs and risks of each energy source, integrated over time and as a function of the total energy produced from that source.

2. Seek alternative strategies within each category of energy supply to reduce the significant costs.

3. Sum the minimized costs within each category.

4. Determine, if possible, the costs of controlling the rate of increase in electricity consumption.

5. Estimate the costs of developing new sources of energy (solar, fusion, etc.) and extrapolate, if possible, the merits of the new sources relative to existing sources.

6. Determine an overall strategy that minimizes the time-integrated costs relative to the benefits.

It is important that one of the products of the analysis be a listing of the true costs of the elements in all the fuel cycles which are commonly considered by the public to be particularly dangerous or the costs of which have not received adequate attention. This should help the public to assess the validity of the decisions in relation to their fears and to base their own decisions on rational choices.

Thus, benefit-cost analysis of various kinds of power production may well include not only the costs and benefits of providing electrical energy from competing sources, but also the costs and benefits to society of using more or less energy, i.e., of having all of the energy it demands as compared with having an energy shortage. Consequences of energy surplus or shortage which require value judgments are outside the scope of benefit-cost analysis as considered here.

C. Methodology

In considering the appropriate methodology for application to the benefit-cost comparison of nuclear versus fossil-fueled power, it is useful to begin with the concept of "lowest practicable level" (see p. 18, Ref. 2) of radiation for regulation or control guidelines.

Regarding the point sources, the criteria used in conventional benefit-cost analysis, stated in inverted order in ICRP #22 (1), are that the total benefit associated with an irradiating activity must be greater than its total cost and that radiation reduction through control practices must be pressed to the point at which the benefits from further radiation reduction (residual damage reduction) no longer exceed the cost of achieving the reduced radiation.

In the case of radiation and radiation control benefits and costs associated with nuclear power, radiation exposure of a population is a cost and the control of this radiation is a benefit. The excess radiation with which we are concerned as a cost is that released outside the reactor and from which there are no benefits.

As noted earlier (p. 74), if the market-determined costs of factor services and product prices represent their total social costs and benefits, there is no need for complicated additional benefit-cost analysis. When there are incidental costs incurred or benefits received by parties not involved in the market transactions, we have "extra-market" costs and benefits, or "externalities," that must be evaluated to determine whether the activities in question are worth undertaking (i.e., total social benefits exceed total social costs).

In the nuclear power cycle, ionizing radiations occur as an unwanted by-product of the generation of electric power. Some individuals will risk being irradiated or will suffer the consequences of radiation who were not parties to any of the market transactions involving purchase of factor services. Thus, there is need to evaluate the additional costs and benefits (if any) from the production of electricity by means of nuclear reaction.

If all of the externalities associated with nuclear power were confined to the operations of the nuclear reactor proper, it would be necessary to estimate only the extra-market costs at the reactor site. However, since there are somewhat similar side-effects associated with activities at various stages in the fuel cycle, e.g., mining, and reprocessing of spent fuel, where such extra-market phenomena are significant, a comparable benefit-cost analysis needs to be undertaken to correct the market indicated costs of such activities at the relevant stages in the fuel cycle.

For purposes of clarification regarding market-compensated contrasted with extra-market costs, we can refer to the case of coal mining. Given widespread current knowledge of the occupational hazards, the risk-mitigating practices instituted (such as better ventilation), and the residual risks, it is reasonable to assume that the increased probability of adverse health effects in coal mining are now, or will eventually be, incorporated in a differential scale of pay as compared with occupations having a lower probability of adverse health effects. Accordingly, if this side-effect of mining were fully market compensated, the total social cost of the intermediate product would be reflected in its market valuation. There would be no need to carry out complicated estimates of health-related costs unless third parties were affected as a result of the resource extraction activity.

To summarize, the benefit-cost analysis associated with nuclear power production needs to include not only the operations of the reactor proper but also the activities at various stages in the fuel cycle at which nonmarket-compensated costs, i.e., authentic externalities, arise. For instance, the analysis would include the health costs of persons affected by environmental contamination but not of those nuclear plant employees who had voluntarily assumed a given health risk in exchange for higher pay.

Another feature of the benefit-cost analysis of nuclear power requires attention, since there is, at the present time, an adequate technical substitute for nuclear reaction in electric power production (fossil fuel combustion). The end product, i.e., electricity, is the same for both. Typically, when alternative technologies exist that produce indistinguishable final consumption services, we regard the benefits as identical. With benefits identical, the only area for evaluation is the relative costs of the two (or more) technologies; and the advantage or benefit (if any) of one can be no greater than the savings in costs (if any) over the most economical alternative.

Accordingly, to determine whether the total benefit from a nuclear power plant exceeds its total cost, it is essential to compare its total cost with the corresponding cost of the most economical alternative technology. This, in effect, may represent the necessary evaluation to achieve the "lowest practicable level" when we consider the problem in the context of the ambient environment rather than radioactive releases at a point source.

When it becomes necessary to consider two or more fuel cycles in defining the lowest practicable level, we have also to determine their optimal mix. Typically, this has been done by projecting "requirements" at historic growth rates and simulating the growth of the power system using several expansion strategies. However, different considerations will arise in the future if the assimilative capacity of the environment is overtaxed. At this point, conservation strategies, as well as non-conservation (production) technologies, must be considered among the alternatives. It is likely that over some energy growth ranges conservation actions can be taken to make additions to the power system unnecessary and at lower social cost than the cost of expanding the power system. This would be of relevance to defining "lowest practicable level" for ambient conditions (2).

As noted earlier, it is outside the scope of this report to specify in detail the methodology that would permit continuous optimization over time allowing for conservation as well as expansion technologies in optimal mixes. However, useful elements of the total problem can be factored out for attention. One feature of the problem generally not encountered, or treated, in conventional benefit-cost analysis involves the continuing impact of accumulating long-lived radioactive effluents on large populations. Also not treated are the potentially different implications for mutagenesis and carcinogenesis of the effluents from alternative fuel cycles. Typically, the social cost of the continuing environmental burden has not previously been taken into account. (For a related problem in which this has been taken into account see references 3, 4, and 5.) All of these are irreversibilities. Accordingly, the evaluation of the cost of an irreversible decision, and the cost of bearing the risk associated with such when taken in the face of uncertain future conditions (6), is an area of peculiar relevance to the evaluation of nuclear power and the objective of reducing radiation to the lowest practicable level both at source points and in the ambient environment.

The mathematical treatment of problems associated with distribution and uncertainty is given in Chapter III. From it, we draw two conclusions: (1) Even if we can legitimately accept (or ignore) the distributional effects of a program involving radiation exposure, including the intergenerational effects, measurement of the expected value of the costs of the exposure will probably not capture the full value of the costs, due to the risk aversion of the affected individuals; and, (2) the unusual time distribution of the costs and their potential magnitude raise serious questions about the appropriateness of following standard practice discounting all benefits and costs and looking only at their present value.

D. The Consideration of Benefit-Cost Analysis in a Comparison of Nuclear Power with Fossil-Fueled Power

We have seen from the foregoing that there are difficult and unresolved theoretical issues in the application of benefit-cost analysis to power generation. Since the benefit-cost estimates involve extra-market health and non-health environmental costs as well as market determined costs and prices, how feasible does such a benefit-cost analysis appear? With consideration of the *benefits* of power deferred for the moment, our interest centers on the *feasibility of* an undertaking to measure the total social cost--including human health and non-health environmental costs--whether arising from radiation, other kinds of pollutants having health implications, or other forms of environmental degradation that may not be related to adverse health effects.

The undertaking of such a measurement is a large effort. At least two such efforts have been commissioned to evaluate the social costs of the fuel cycle technologies underlying the generation of electric power. One by a group at the Argonne National Laboratory (ANL) is a completed study the results of which were published in 1973 (8); the other, by a group at the Brookhaven National Laboratory (BNL), is still in progress, with only a preliminary report (in the nature of an interim progress report) available for review (9). The ANL study, entitled *Social Costs for Alternative Means of Electric Power Generation for 1980 and 1990*, *provides a basis for assessing the feasibility question we have raised.*

The ANL study attempts estimates of the relevant costs for each of the fossil fuel cycles--coal, oil, and gas--for two light water nuclear reactors, and for the high-temperature gas-cooled slow, and the liquid-metal-cooled fast, breeder reactors. Two sets of data are presented for each fuel cycle, i.e., health and accident effects, and non-health environmental effects for each of the several fuel cycles basically in biomedical and/or physical terms; and, ultimately, an attempted transformation to the extent possible, of all human and natural resource impacts, whether market incurred or extra-market, into monetary units to represent social costs.

Since it is likely that there are extra-market environmental effects associated with each stage of each of the several fuel cycles, estimates are provided for the mining, refining (where applicable), transportation and energy conversion stages, for the fossil fuel cycles; and for mining, milling and fuel fabrication, the reactor proper, and the reprocessing stage including the transportation of spent fuel to the reprocessing plant and the return shipment of materials from it to the power plant, for the nuclear fuel cycles. An example illustrating activities, environmental agents or factors, and their effects where it is possible to do so for a coal-fired power plant (1980), is shown in Table V.1, reproduced from the ANL study.

At the top are shown the conventional market costs such as for capital services, fuel, and standard operating and maintenance costs. These include all of the internal costs of the power plant operation, and include in part some of the social costs of occupational hazards to the extent these are

TABLE V.1
(From Reference 8)

Annual Effect of 1000 MWe Coal-Fired Power Plant Operation in 1980

	Mining	Transportation	Power Plant	Total
Conventional costs (10^6 \$)				
Fuel	21	8		29
Capital			55	55
O & M			7	7
Occupational accidents				
Deaths	0.98[a]	0.055	0.03	1.1
Non-fatal injuries	40.5[a]	5.1	1.5	47.1
Mandays lost	8330[a]	570	350	9250
Mining[a]				
Land disturbance by stripping (acres)	300			
Land subsidence, underground mining (acres)	200			
Mine drainage, tons	10,000			
Sulfuric acid in drainage, tons	80			
Dissolved iron in drainage, tons	20			
Rail Transportation				
Public death		0.55		
Injury		1.17		
Days lost		3,500		
Transportation and Handling loss, tons		10,000		
Ash collected, tons			250,000	
Sulfur retained, tons			46,000	
Waste storage area, (acres)			5	
Thermal Discharge, 10^{10} kWh(t)			0.69	
Stack Discharge, 10^{10} kWh(t)			0.16	
Air Emissions, tons:				
Flyash			2,000	
Sulfur dioxide			24,000	
Carbon dioxide			6,000,000	
Carbon monoxide			700	
Nitrogen oxides (as NO_2)			20,000	
Mercury			5	
Beryllium			0.4	
Arsenic			5	
Cadmium			0.001	
Lead			0.2	
Nickel			0.5	
Radium 226, Ci			0.02	
Radium 228, Ci			0.006	
Facilities land use, acres[b]				150

[a] - 50% of production from strip mining and 50% from underground mining.

[b] - facilities are for two generating units at a site and include fuel preparation but exclude transportation area.

reflected in differential pay scales and incorporated into the price of the coal delivered to the power plant.

Subsequent row entries include occupational hazards converted into annual estimates of workdays lost and other aspects of environmental deterioration due to the activities at each of the stages of the fuel cycle associated with a 1000 MWe power plant. Stack emissions from burning a 1980 "representative" coal mix are given, but no effort is made to estimate the fraction of the population affected based on the distribution of such emissions, nor is any attempt made to estimate mortality or morbidity resulting from the health effects of the combustion products of coal emitted from the stacks. It should be noted that environmental effects are given in terms of final impacts in some cases (even ultimately transformed into monetary units in the case of conventional costs) and in other cases simply as agents that have unspecified effect on the environment such as arsenic, mercury and sulfur dioxide measured in tons, or landscape degradation in terms of acres of land disturbed. In short, effects are measured in several dimensions; dollars, workdays, tons, acres and even curies. The conversion of these into a common unit of measure will be discussed below, after examination of the corresponding Table V.2 for a pressurized light water reactor (PWR), also taken from the ANL study (8).

Again, we have the conventional costs, some part of which may represent internalized costs of some of the occupational hazards shown in subsequent row enteries. These occupational hazards, and non-health or accident related environmental effects, again, are presented in a variety of units of measure seemingly appropriate for description of physical or biomedical effects associated with the various activities at the several stages in the PWR fuel cycle.

In Table V.3 following, we reproduce the data in which attempts were made to monetize the physical and/or biological effects to the extent possible, allocated between external and internal costs for the coal fuel cycle. It should be noted that a half of all occupational hazard losses are attributable to "conventional" or market costs--the other half to external costs that are included in total social costs. The division between internal and external costs was said to be arbitrary by the authors of the ANL study. Accidental deaths were taken, as suggested by Bureau of Labor Statistics sources, to average 6,000 lost working days per case, and an arbitrary $50 per day was taken as the monetary value of the loss. An argument was advanced for discounting the stream of losses experienced over time, but this was not done--and, as discussed above, it is not altogether clear why there should be a discounting of lives, and if not, why their value should be monetized. In any event, sensitivity analysis conducted with values set both at one-half and double the monetized value are purported to affect the outcome of the study negligibly.

For landscape degradation associated with coal mining, it was assumed, in the ANL study, that ten percent of the coal production would come from contour mining, 40 percent from area strip mining, and 50 percent from underground mines. Costs of restoration were treated as if they had been incurred by the mine operators and reflected as internal costs in the price of coal.

TABLE V.2
(From Reference 8)
Annual Effect of 1000 MWe PWR Operation in 1980

	Mining	Milling - Fabrication[a]	Reactor	Reprocessing & Transportation[b]	Total
Conventional Cost (10^6 $)	1.9	7.9	68.8	1.4	80.0
Occupational Accidents					
deaths	0.09	.005	.01	.002	0.1
nonfatal injuries	3.6	1.5	1.3	.12	6.5
mandays lost	762	88	110	15	975
Public Casualties From Transportation					
deaths	-	-	-	.009	.009
nonfatal injuries	-	-	-	.08	.08
mandays lost	-	-	-	60	60
Miners radiation exposure (WLM)	110	-	-	-	110
Other occupational exposure (man-rad)	-	15	300	30	345
Tailings produced at mill (10^3 MT)	-	79	-	-	79
Solid radioactive waste disposal (10^2 ft^3)	-	77	22	13	110
Cost of transportation accidents (10^3 $)	-	-	-	1.6	1.6
Cost of fab. & repro. accidents (10^3 $)	-	.03	-	.03	.06
Facilities land use (acres)[c]	-	-		-	300
Strip mining of uranium and mill tailings (acres)	5.5	2.2	-	-	7.7
Burial of solid radioactive wastes (acres)	-	.15	.04	.31	0.5
Net destruction of uranium (MT)	-	-	1.1	-	1.1
Thermal discharge (10^{10} kWh(t))	-	-	1.4	-	1.4
(10^3 MW(t))	-	-	2.1	-	2.1
Population exposure from reactor accidents other than Class 9 (man-rem)		-	2	-	2
Radioactive releases to atmosphere (Ci)					
H-3	-	-	-	16000	16000
Kr-85	-	-	5500	28000	29000
I-129	-	-	-	.0003	.0003
I-131	-	-	-	.004	.004
Xe-131m	-	-	180	50	230
Xe-133	-	-	580	-	580
Cs-134	-	-	-	.007	.007
Rn-222	-	44	-	-	44
U-234	-	.006	-	~0	.006
U-238	-	.002	-	~0	.002
Total U	-	.009	-	~0	.009
Pu-241	-	-	-	.003	.003
Total Pu	-	-	-	.003	.003
Others	-	-	-	.2	.2
Radioactive releases to waterways (Ci)					
H-3	-	-	580	350	930
I-129	-	-	-	.0002	.0002
I-131	-	-	.03	.00002	.03
Cs-134	-	-	.01	.01	.02
U-234	-	.1	-	.002	.1
U-238	-	.04	-	.0007	.04
Total U	-	.2	-	.003	.2
Others	-	.0008	.1	3.	3.

---

[a] Milling, Conversion, Enrichment, and Preparation and Frabrication

[b] Reprocessing and all Transportation steps.

[c] Facilities are for two generating units at a site and include fuel preparation and recovery but exclude transportation area.

TABLE V.3
(From Reference 8)
Evaluated Effects of 1000 MWe Coal-Fired Power Plant Operation in 1980

Category	Comment	Internal Effects 10^6 $	Internal Effects MDL	External Effects 10^6 $	External Effects MDL*
Conventional Cost					
Capital	Internal	55	-	-	-
O & M		7	-	-	-
Fuel		29	-	-	-
Mining & Transportation					
Contour Strip	10% of production for 1000 MWe plant The external cost associated with uprooting families and reclamation has been estimated.	-	-	0.1	-
Area Strip	40% of production. Roughly 250 acres--external cost taken to be $500/acre.	-	-	0.1	-
Underground	1/2 of production. Roughly 200 acres--mine deep enough that subsidence does not effect property.	-	-	∿ 0	
Mine Drainage	From the report, Acid Mine Drainage in Appalachia, $3.5 million for 500 billion gallons of drainage. For 2.4 million gallons the cost is $20.	-	-	∿ 0	-
Transportation					
Loss of coal	10,000 tons at $9/ton.	C	-	-	-
Non-employee accidents	50% external assumed.	C	1750	0.09	1750
Power Plant					
Thermal Discharge	1.3 million kWt.	-	-	0.4	-
Pollution Damage	SO_2 and particulates.	-	-	0.8	U
Other Pollutants	External not evaluated.	-	-	U	U
All Occupational Accidents	50% external assumed.				
Strip Mining			650		650
Underground Mining			3500		3500
Transportation			300		300
Power Plant			170		180
	Total Occupational Accidents	C	4620	0.23	4630

*MDL -- man-days lost. U -- unevaluated C -- included in conventional cost

Attention was given to displacement of individuals as a result of strip mining deposits underlying their lands, and this charged to social costs appearing as an externality.

One serious deficiency in the attempt to provide comprehensive coverage in monetized values of extra market impacts, was the inability of the authors to find a basis for a quantitative estimate of adverse health effects from stack emissions of sulfur dioxide, nitrogen oxide, and other products of fossil fuel combustion. To this extent the estimated social cost of the fossil fuel cycle is incomplete--a deficiency in addition to the possibly inadequate estimates of some categories of evaluated social costs.

An example of the attempt to monetize the physical and biological effect of the nuclear fuel cycle (PWR) is shown in Table V.4. The occupational accidents and disabilities are allocated, as in the fossil fuel cycle, half to internal (conventional) and half to extra-market components of social costs. All of the potential adverse effects from radiation throughout all stages are evaluated, except for the class 9 accident--which at the time of the ANL report preparation was under study by the Rasmussen group, and with publication of the Rasmussen Report (10) could now be included.

Considerable disagreement is already apparent in the estimation of the risk of major catastrophies in commercial nuclear power plants. Where such disagreement is important, preventative steps will need to be taken to nullify the effects of any incorrect estimate of the risk. The costs of these preventative steps will appear as "costs" of the unquantifiable risk. For example, the effects of a catastrophic release of radioactive materials which could occur on a loss of collant accident in a light water reactor might be considerably reduced by placing reactors in regions of low population density. Much of the cost of this major risk of uncertain magnitude would then be apparent as a finite increase in cost of power transmission needed to reduce the upper estimate of the risk to an acceptable level.

While the environmental dose commitment of radionuclides is illustrated for tritium, and krypton, the total global dose commitment for all radionuclides was not undertaken. An EPA study (1974) (11) includes materials that could lead one to believe the effects of the excluded radionuclides, the actinides in particular, could be of greater long run consequence than the included tritium and krypton. A recent study by Cohen (12) takes a position contrary to the EPA Study (1974).

Accidental loss of life and premature deaths associated with the PWR cycle were treated similarly with the coal cycle. That is, a death was assumed to result in an average 6000 mandays lost and a manday was valued at $50. There are serious problems with efforts to place a value on a life as we know. Ideally, it would be preferable to have an expression from each individual as to how much he would need to be compensated to have some low probability of premature death or some specified adverse health effect increased by some appropriately small amount. In this way, it would be possible to avoid having an individual place a value on a life other than his own, and in this case the expression would be in terms of increasing by a specified amount a low probability

TABLE V.4
(From Reference 8)

Evaluated Effects of 1000 MWe Operation in 1980

Item	Comment	Internal Effects millions $	Internal Effects mandays lost	External Effects millions $	External Effects mandays lost
Conventional Cost					
Capital	internal	60	-	-	-
O & M		6	-	-	-
Fuel		14	-	-	-
Occupational accidents	50% external assumed	C	488	.024	488
Non-employee accidents during transportation	50% external assumed	C	30	.0015	38
Miners radiation exposure	future deaths--50% ext.	C	33	.002	33
Other occupational exposure	future deaths--50% ext.	C	207	.01	207
Population exposure from reactor accidents other than Class 9	future death--all ext.	-	-	.0001	2
Population exposure from Class 9 reactor accidents		U	U	U	U
Population exposure from the evaluated normal releases	future deaths--all ext.	-	-	.0095	190*
Cost of transportation accidents	almost completely int.	U	-	-	-
Cost of fabrication accidents	almost completely int.	C	-	-	-
Cost of reprocessing accidents	almost completely int.	C	-	-	-
Thermal discharge at reactor	external	-	-	0.6	-
Genetic effects from radiation exposure	external Public	-	-	0.014	290
	Occupational	-	-	0.48	920

C-covered in the conventional cost, for example, by insurance payments. U-unevaluated of premature death or disability. This, of course, appears not to be practicable, less so for the general population that might be exposed to low levels of ionizing radiations even than for the exposed occupational groups, and absolutely impossible for those who are the yet unborn victims of genetic effects induced by radiation releases to the environment. Accordingly, while it is desirable to avoid having to depend on a procedure something like that employed in the ANL report, if some common unit of measure is ultimately required, it may not be possible to avoid it as a pragmatic matter, although the specific value and its rationalization need not be accepted.

The use of the 6000 workdays at $50 a day, if accepted, still does not eliminate problems in connection with its application. We must remember that the monetized value is only a surrogate for the loss of life for the great bulk of the mandays lost. If we regard life as of value in a sense different from the embodiment of factor services, or labor, we should then question the appropriateness of discounting the value associated with life because of the time of its demise. Accordingly, the differential value employed for somatic and genetic effects ($300,000 v. $100,000) in the ANL study also might be questioned quite apart from the essentially arbitrary basis for the calculation of the surrogate monetized amount.

There is also the question of the appropriate range of estimates of the local and global doses of radiation when the entire family of long-lived radionuclides released into the environment is considered. These may increase greatly the adverse health effects from radiation but whether or not they will do so is subject to considerable uncertainty. Accordingly, the uncertainty surrounding the effects of the environmental dose commitment of the long-lived radionuclides was not treated by the ANL report in its assessment of the cost of nuclear power production.

As noted above, an uncertainty in estimating certain risks does not necessarily prevent one from making an estimate of the costs of reducing the risk. For example, the dangers to the public of the inadvertent release of radioactive contaminants and the exposure of some members of the nuclear labor force to large amounts of radiation are likely to be reduced if reprocessing of spent fuel is not attempted at this time. Selection of this method of reducing these risks would appear as costs in various ways, such as an increase in the price of uranium when easily recoverable supplies are exhausted and the cost of stock-piling spent fuel. The time-integrated national cost might, however, be reduced since better technologies for reprocessing are likely to be developed, or the need to reprocess will disappear as new sources of energy become available.

There are several subjects that are not treated in the ANL report. Two of them are the storage of long-lived radioactive wastes and the security of all radioactive material in transit as well as in storage. In view of the intense controversy these subjects have generated, some explicit attention to the risks and costs they involve is in order. A third untreated subject is the preproduction costs in the nuclear cycle; that is, the very large investment in R&D that lies behind the construction and operation of nuclear plants. A fourth is the cost of regulation, on both the nuclear and fossil fuel scores. If the analysis is to be truly complete, all of these items should be included.

E. The Feasibility of Benefit-Cost Analysis as a Means of Comparing Nuclear vs. Fossil Fuel Power Cycles

As stated in the preceding section, the ANL study provides a basis for assessing the applicability of benefit-cost analysis to the problem at hand. It constitutes an exhaustive and meticulous attempt to make such an application. Yet it is clear that at this stage the reckoning of the social costs in the analysis is seriously incomplete. Presumably, using the ANL study as a point of departure, the missing elements of the analysis might be capable of development with further effort, and other elements that may be deficient in treatment at this time might be more adequately addressed following constructive criticism and research, or a consensus on the conventions which need to be adopted.

Yet even if all these matters were to be successfully resolved it would not necessarily refine the analysis sufficiently to have identified the optimal point between radiation control practice and radiation damage reduction, or the costs involved. That is, what we have in the ANL study is only one point on each of the cost curves relating social cost to output (electricity from a 1000 MWe power plant operating at an assumed 75 percent plant factor), without explicit consideration of the relation between radiation control and radiation damage reduction. The issue of accuracy aside, Tables V.3 and V.4 in the preceding section suggest that the social cost of the evaluated cost elements of nuclear are less than the social costs of the evaluated elements of the coal fuel cycle, given the mix of coal and nuclear assumed for the ANL study. But in neither case have the control costs of pollutants been adjusted at the margins nor the pollution damage been assessed. One reason is that we have no convincing measures of the costs and benefits of reducing the emissions of toxic substances associated with energy production.

There appear to be several possible approaches. One is to attempt first to develop adequate dose response relationships for non-radiation pollutants (products of fossil fuel combustion) to a level comparable with the dose response relationships available in connection with radiation. Then the analysis could be refined to include comparison of incremental control costs with damage reduction for all types of pollutants, including radiation, for both fossil and nuclear systems.

Even this would relate to only the point source, "local optimum" aspect of the problem. If the radiation at that point will still contain releases into the environment of long-lived radionuclides that do not have permanent natural sinks from which they will not be resuspended to become health risks again, it is likely that the relation of social costs among the various fuel cycles will be subject to change over time. To provide at any time the optimal mix among fuel cycles represents an incredibly complex dynamic optimization problem, which suggests that benefit-cost analysis may not be equal to the problem. Indeed, given the degree of uncertainty inherent in the problem it may never be possible to answer some of the relevant questions completely. For example, the estimates of social costs of the fuel cycles were predicated on the assumption of properly functioning plant and equipment. Built-in backstop safety features to abort adverse effects of malfunctions were included. However, to further allay concerns about serious accidents occurring at the reactor proper, redundant emergency safety systems may be required extensively as backstop fail-safe measures. It is this apparent need for redundancy in backstop emergency systems, to reduce even more a low probability of a catastrophic accident, that is at least partly responsible for the mounting costs of nuclear reactors in recent years. For this and other reasons, it would appear that our estimates of costs are not particularly firm, even aside from the dynamic optimization problem.

But quite apart from the increasing costs of providing fail-safe technological systems, there are problems associated with the possibility of "malfunctioning personnel" at critical stages of the nuclear fuel cycle --and perhaps equally serious "malfunctioning members of society" bent on achieving objectives through violent means. In the study by Willrich and Taylor (1974) (13) the problem of deliberate sabotage and theft is analyzed and the suggestion emerges that a disciplined terrorist organization, for example, could misappropriate enough fissionable material and command the technical capability to fashion a crude nuclear explosive. As the scale and extent of the nuclear power industry increase, other things remaining equal, opportunities for diversion of potentially (socially) hazardous radioactive materials will increase. This is particularly true as fission technology expands outside of control of the U.S. Government, in part, it is likely, to areas of political instability. Less progress has been made in the design and stability of fail-safe social systems and universally accepted social contracts than in the design of technological systems.

When the scope of social costs is extended to include differential susceptibility to sabotage between different energy conversion technologies, some would hold that the approach that focuses narrowly on the conventional elements of benefit-cost analysis is inappropriate to the problem (14). We believe, however, that the issue is not a technical one in which conventional comparison of resource costs among alternatives alone is at issue, but that in addition to this economic analysis, there is need for a process of choice that will consider ethical and political as well as economic issues, in which the larger concerned public is intimately involved.

F. Conclusions

We have seen that the application of formal benefit-cost analysis to the trade-off between nuclear and fossil fueled power suffers from severe limitations, some of which are due to data imperfections, others to the nature of the method. Does this mean that it is of little or no use in decision-making and policy formulation? In giving the answer to this question, it is helpful to review the major shortcomings of benefit/cost analysis and the results of its application.

It was noted at the beginning of this chapter that the analysis would not include the treatment of conservation through government policy (as distinguished from individually motivated conservation). The reasons for this exclusion should now be apparent: the difficulties are too great. If the policy being considered as an element in the benefit-cost analysis is the deferral of present consumption of energy resources in favor of the benefits that will accrue to society in the future, those beneifts, as we have seen, cannot be treated in present value terms. But what weight should then be given to them? We do not know how to reach an objective answer to this question.

The preceding discussion also emphasizes the difficulty or impossibility of attempting to reduce many disparate elements to the common denominator of the dollar value. Equally troublesome (and in the end probably a more immediately serious shortcoming) is the inability to deal with unknowns and uncertainties in assessing the effects of the different fuel cycles, both fossil and nuclear. How does one treat the carbon dioxide effect, for example? Does the continued and increasing use of fossil fuels threaten to reduce average world temperatures? Although there are opinions on both sides, no one knows. Does the continued expansion of power generation threaten to alter the earth's heat balance? Again, no one knows. What is the long-term effect of submicron ash particles from coal combustion? Are there synergistic effects? What are the somatic effects on future generations of exposure of the present generation to radioactivity (whether from nuclear or fossil-fueled generation)? Can nuclear waste products be adequately sequestered until they are no longer hazardous?

With time, the number and degree of such uncertainties should diminish. Thus, the fact that the analysis must remain "unfinished" given the present state of knowledge does not mean that it cannot be done better in the future. It is, therefore, important to identify the uncertainties as far as possible, so that unknowns do not remain unknown unknowns.

Where does this leave benefit-cost analysis? At the lower levels of decision-making, where the decisions are largely technical, it is indispensable. As one proceeds up the successive levels of decision-making, policy decisions must inevitably include more value judgments, and at these levels the usefulness of traditional benefit-cost analysis tends to recede from that of providing criteria of choice to that of providing ancillary information. Benefit-cost analysis is economic analysis, and where the science of economics is inapplicable, so, too, is the benefit-cost comparison in the formal sense.

We conclude, nevertheless, that, in light of the charge to which we have addressed ourselves, benefit-cost analysis applied to the choice between nuclear and fossil-fueled power may have some value. Although formal benefit-cost analysis cannot yield results which, in effect, make possible objective decisions at higher policy levels the exercise is nonetheless useful in formalizing the comparison to the extent possible and in identifying and making explicit the value judgments implied in a decision, thus enlarging the basis of knowledge to which, in the end, ethical judgments must be applied.

CHAPTER V

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CHAPTER VI

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CHAPTER VI

BENEFIT-COST ANALYSIS FOR MEDICAL RADIATION

A. Summary and Recommendations

1. Summary

The chapter reviews briefly the risks and economic costs of medical radiation--diagnostic radiology as well as nuclear medicine and radiation therapy--in terms of somatic and inheritable disease and direct and indirect dollar costs of radiological health care services. The ethical considerations relating to radiation protection are placed in perspective as regards exposures to patients in the present day patterns of the practice of medicine in the United States. Certain general concepts are introduced which aid in the development of benefit-cost models and which apply solely to the use of ionizing radiations in diagnosis and therapy in our health services systems. These include the impact of societal decision-making relative to the health and well-being of the individual in society and society as a whole and, thus, the perception of risk and disease as it affects society and its efforts to improve the quality of life. The models developed are based primarily on the economic cost of illness and are designed to achieve a benefit-cost relationship. To quantify this relationship, insofar as possible, dollar valuation has been used. This method represents only one form of calculating a relative value. The values cited are illustrative of the analytical process only and are not to be taken as actual measures.

The models developed are imprecise and general. The unifying simplicity achieved by application to a single common unit, the dollar, relates costs (resources used by society to achieve its aims, viz., radiological health care delivery) to benefits to be derived (improved quality of life, involvement in societal productivity, etc.) by the individual and by society. The prevention of disease and the failure to cure existing ill-health is considered in terms of the loss of human resources, e.g., present and future lives saved, human productivity, etc. In this model, the reduction of radiation risk is considered as a means to achieve improvement in the benefit-cost ratio.

Specific examples are used in the application of these models: (1) in diagnostic radiology, mass screening surveys (e.g., mammography) and certain high dose procedures; (2) in radiation therapy, the treatment of cancer. In these models, valuation is inescapable, but economic terms are used only to achieve an arithmetic method readily understood by society.

The reduction of risk model is developed using a reduction of dose method; models are described to achieve this without reduction of potential benefits of medical radiation to the individual and to society. An approach to the development of alternative technologies and methodologies in the radiation sciences is considered briefly. Appendices are included to assess the value of the genetically significant dose and the status of federal and state regulations.

2. Recommendations

a. Benefit-cost analysis should be used in decision-making relative to medical radiation and health care delivery to large populations in society. Dollar valuation, which should be used only as a relative value, provides a method to relate all direct and indirect costs to the benefits accrued. Methods for benefit-cost analysis for medical radiation based solely on the economic costs of illness and evaluation of human life are limited and may apply to society as a whole for decision-making in the allocation of limited resources available; these methods do not necessarily apply in specific circumstances of health and illness to single individuals.

b. Efforts should be directed to improving the benefit-cost ratio, without limiting the benefits derived from modern radiological services to society. The benefit-cost ratios for medical radiation may be improved without loss of benefit by decreasing the potential health risks through dose reduction methods, e.g., shielding of radiosensitive tissues, improving imaging systems and elimination of unnecessary exposures to large populations.

c. The role of diagnostic x-ray examinations in medicine and dentistry, particularly in children must receive careful study before a full understanding of the benefits and the costs to the individual and to society can be determined.

d. Careful benefit-cost analysis should be done prior to carrying out mass x-ray screening programs of large populations.

B. Introduction

Medical radiation represents the largest source of man-made radiation exposure to the general population at the present time (1,2). This exposure is almost exclusively to low LET radiations from the diagnostic use of x-rays and radioisotopes and the therapeutic use of x-rays and radioactive source materials, such as cobalt-60 or radium. In the 1960's, the average yearly radiation dose to the U.S. population from medical exposure was in the range of 60-100 mrem per person compared with approximately 100-125 mrem from natural background (1,3). Large numbers of persons receive diagnostic radiological x-ray examinations, and these x-ray exposures represent the main source of radiation dose to the population from medical radiation (see Table VI.1) (1,3). Therapeutic radiation for neoplastic and non-neoplastic diseases

TABLE VI.1

USPHS X-Ray Exposure Study - 1970 (3)

	(million)
Population of United States	200
Number of x-ray visits	179
Number of persons receiving one or more x-ray procedures	130
Number of x-ray examinations performed	212
Number of medical x-ray visits	112
Number of medical x-ray examinations	140
Number of dental x-ray visits	68
Number of dental x-ray examinations	70

contributes only a small proportion of the average yearly radiation dose, whereas exposure from radioactive isotopes in nuclear medicine provides only a fraction of this value (3).

Total health care spending in the United States in 1974 amounted to $104 billion, an increase from $83 billion estimated for 1972 and $94 billion in 1973 (4,5). Medical care spending claims more than 7.5 percent of the Gross National Product, which in 1974 exceeded $1.35 trillion. The average health expenditure per person in 1974 was $485, almost two-thirds of which was for hospital care and physician's services. Radiological health care delivery for diagnosis and treatment claims approximately 7 percent of the total annual health care spending, about $7 billion.

In 1974, approximately 140,000 medical x-ray machines and 143,000 dental x-ray machines were in use in the United States (6). In addition, some 7,500 non-medical x-ray, fluroscopic and analytical x-ray devices were being used in industry, research, and education. Currently, some two-thirds of the population of the United States receives a medical radiological procedure each year (3).

Since 1962, the number of hospitals in the United States with clinical radioisotope facilities has more than doubled, from 1,500 to well over 3,000. In this decade, the growth rate has been linear, increasing by 50 percent during the first five years. During the 1973-1975 interval, it was estimated that the sale of medical radiopharmaceuticals and nuclear medical instruments rose from $110 million to $200 million. From 1971 through 1974, the estimated number of organ scanning and function procedures rose from 4 million to 9 million.

C. Risks from Medical Radiation

Estimates of the somatic and genetic risks from radiation have been provided by the NAS-BEIR Committee (1), ICRP (7), and the UNSCEAR (2). In view of gaps in our knowledge of the dose-effect relationship in the human situation, the linear non-threshold hypothesis has been used in assessing somatic and genetic risks in regard to human radiation protection (1).

D. Ethical Considerations in Medical Radiation

The uses of radiation in medicine may be categorized as diagnostic and therapeutic, and investigational. The goal of these medical uses of radiation is to achieve maximum health benefits, and this goal must be weighed in the context of a broader mission of seeking maximum well-being of society. In this broader frame, health benefits must be weighed against costs. The costs themselves include both health hazards and economic costs, services and resources. In addition to information on the costs and benefits, a benefit-cost evaluation requires a relative value system, a method for trade-offs. Its implementation requires an informed society capable of understanding the values.

For medical radiation, as well as for certain uses of radiation in energy production, the problem of balancing benefits and costs is complicated by issues of ethics and discrimination. As an example, increased years of life expectation or increased economic productivity can be a useful measure of health benefit in some contexts. If, however, these parameters are used to balance the benefit-cost equation against the elderly with limited life expectancy or those with limited productivity, important values of society will have been overlooked.

The problem of evaluating medical uses of radiation is further complicated by historical considerations. The introduction of radiological techniques in medicine has led to a dependency on its application in both diagnosis and therapy, particularly in cancer therapy. Throughout most of the decades since its introduction, the measure of the health hazard from radiation has been only poorly known and even now many issues remain unclear, particularly with relation to the hazard of exposure at low doses. Furthermore, for many of the uses of these radiations, health benefits have been dramatic, particularly when used in diagnosis of suspected medical conditions of major morbidity and in treatment of cancer. For these uses, it has been assumed, probably correctly, that no formal evaluation was necessary to determine the direction of the benefit-cost balance. For certain other uses, for example, in diagnostic x-ray screening of persons in whom there is no suspicion of disease or in therapy of many non-neoplastic conditions, the balance of values is less clear. However, here, too, decisions have commonly been made on the basis of informal evaluation.

Costs to be balanced against benefits include health hazards, costs of services, and costs of resources. Principal decisions may require choices among these complex costs. As an example, the costly technology of radiation protection requires a determination of the minimal total cost, the sum of the health hazard cost and the radiation protection cost, and all related to a fixed benefit from the medical radiation use. As a further example of the complexity of the cost side of the equation, the health hazard includes both the somatic and the genetic hazard.

A special consideration in the use of medical radiation is the individualized nature of the decisions that must be made. If a decision is made to carry out a diagnostic radiological procedure or to undertake a course of radiotherapy for a given patient, the principal benefit will accrue to this individual. There are general benefits to society from an individual's health, and there are hazards to future generations, but these are usually secondary issues. While the individual must be informed and included in the decision-making, he will in most instances not have sufficient understanding of the issues to contribute meaningfully, and the physician must accept the main burden of making decisions that often vitally affect the individual. This circumstance is contrasted with the decisions to be made relative to uses of radiation in energy production where large populations are involved.

The present basis for radiation protection of the health of the public is essentially the establishment of upper acceptable limits for individual and population exposure and of dose-limiting recommendations and guidance for special cases. These recommendations imply: (1) any biological hazards, both to the individual and to the population, are offset by commensurate benefits; (2) the risks are acceptable both to the individual and to society--this acceptability may best be judged by comparison with other risks encountered in life, though the basis for such comparison is complex; (3) the beneift-cost balance should be made as favorable as possible; and (4) under the assumption of a nonthreshold dose-effect relationship, a health hazard component of the cost must be considered to exist for every radiation use.

Diagnostic and therapeutic radiation are expensive. Costly equipment and hospital facilities, highly trained professional and supporting personnel, and expensive direct and indirect costs, are required to make radiology safe and reliable. Aside from the reduction of risk and any radiation hazards to individuals and the general population, effort should be constantly directed to placing economic considerations into proper perspective. Wasted radiation in medicine is costly to the consumer, and provides no benefit to the individual and future generations. Thus, any deliberate exposure to medical radiation should also be concerned with the balance between benefit and cost, and may be justified by the benefits that are expected to result. Large costs may be reduced, for example by simplifying examinations performed for the immediate medical and dental needs of the patient, by centralizing sophisticated and costly equipment, personnel, facilities, and services for regionalization and delivery of health services to larger populations; by careful benefit-cost analysis of mass x-ray screening surveys for the early detection of specific curable disease, and particularly the early diagnosis of cancer; by the determination of degree of benefit to be derived by the patient examined for occupational, insurance, and medical-legal purposes; and by the assessment of the efficacy of the treatment of non-neoplastic diseases with ionizing radiations.

E. General Concepts and Models of Benefit-Cost Analysis for Medical Radiation

1. Introduction

Health services programs are designed not solely to prevent disease and to improve health, but equally to decrease costs resulting from illness and disease. For example, the benefits of controlling disease may be simply assessed as the current costs of the disease which are thereby averted by the program (8-11), and such benefits, or averted costs, can be listed into three broad categories (12): (1) resource-use, i.e., the actual expenditures on medical care; (2) resource-loss, i.e., the estimated losses of current production or, preferably, human productivity; and (3) resources-transfer, i.e., payments for certain hidden costs transferred from the well to the sick. The pain and discomfort accompanying and following any disease may be included in both resource-use and resource-loss categories.

Quantifying such costs and the symmetrical averted costs then may be achieved roughly by summation of identifiable activities. For example: (1) The direct costs or expenditures on medical care and health services include all costs of the services of physicians, paramedical personnel, drugs, hospital facilities, equipment, etc.; these are both capital and recurring costs and are quantifiable as resource-use. (2) The losses of current production of individuals who are ill, but who otherwise would be well and productive may be determined as resource-losses: (a) the loss of gross earnings resulting from a loss of working hours in order to have diagnosis, treatment, and to be rehabilitated to productive activity, and (b) a reduction in gross earnings as a consequence of the social, psychological, or physical constraints which render a person less productive (or less employable). Here, pain and discomfort associated with disease are not easily quantifiable; the procedure of evaluation of such intangibles is usually arbitrary. (3) Transfers of resources may be determined as costs to the givers and benefits to the receivers; disease takes resources, in the form of cash payments or hidden subsidies, away from those who are well and have paid costs of the program, to those who are ill.

Because of limited economic resources available to society, it is becoming increasingly important to make proper allowances for losses, or gains, arising from changes in the incidence of disablement, disease, or death, and the costs of health services necessary to avert the losses and to improve the gains or benefits. The analysis of saving life may be considered symmetrical with that of losing it. One common analysis of the loss of life, in spite of many dissatisfactions with the method, is the net output method of calculating the economic worth of a person's life and, therefore, the loss to the economy of society consequent upon his illness or death. The analysis may provide a conservative estimate based on an arbitrary value of human life expressed in terms of lifetime earnings, and based on past and present earnings, consumption, and discounting to the present the person's expected future earnings. The loss to the economy takes into account the expected gross earnings, the duration of life expectancy, and the social rate of discount. (An appropriate figure for the value of human life is not easily determined; one figure may be approximately $300,000.00 based on data of the American National Standards Institute (18, i.e., an assumed productive value of $50.00 per day, or a loss of 6,000 working days as a result of accidental death.) Furthermore, the economic value of the non-employed but "productive" housewife may be determined on the same basis of costs for skilled or professional services performed and prorated as household jobs, rather than simply as a domestic helper in the home.

2. Averted Costs

The special problems of quantifying the effects of health services programs is a matter for physicians and health engineers. The health economist is concerned with the problem of valuing the benefits per life saved or illness avoided. In this regard, a death avoided means that a loss of a productive life may be avoided. In other words, the present value of this activity is an economic benefit, and that benefit is credited to the activity for saving life.

An initial step to estimate the value of the measure for saving life or reducing illness, thereby improving health, is to determine what the average individual whose health is improved or life is saved would earn (or produce) over the rest of his life. The following discussion will use principles (9,10,13,14) in which a useful distinction is made between the effects of disability (or loss of working time away from work) and debility (or loss of capacity while at work). However, in each category, the multiplicity of variables, such as life-expectancy and human productivity, preclude calculation of the precise influence of a particular health services program on a subpopulation.

Another approach to benefit-cost analysis infrequently used is to establish that various kinds of risk to health exist, and then decide how much to spend in reducing these various risks. This implies that the individual and society can evaluate diminution in risk. However, the primary purpose of this approach in established health services programs in which risks exist is nevertheless exactly the same as that of the averted cost approach, namely to save lives and reduce illness. This will be discussed later in greater detail.

3. Economic Resources: Benefit-Cost Models

There is a need for clarifying cost concepts in current use to classify and estimate costs of health services. Economic costs, in a limited sense, arise out of the impact of disease and injury upon the use, distribution, and availability of economic resources. One method (11,13) is based on the effects of such health services on the use, distribution, and quantity of available economic resources for health care delivery.

a. Resource-Use Model

The direct costs of health programs involve manpower and material resources required for prevention, diagnosis, treatment, and rehabilitation of each of the major diseases and disabilities. Available estimates indicate that the part of the nation's manpower and of goods and services produced (both public and private expenditures) that is devoted to health care has continued to increase substantially during the past 50 years (4). For example, in 1929, it was estimated that health and medical expenditure was approximately $4 billion, or about 4 percent of the Gross National Product. Since 1965, total national health spending has risen from $39 billion to $56 billion in 1969, to $104 billion in 1974, approaching 8 percent of the Gross National Product (4,5). During the period from 1950, per capita expenditure for health rose from $78 to $485. During the 1960's, there was a steady expansion of federal and state authority in the field of health care. In the 1970's, a primary political objective appears to be attempts to develop a rational system for regulation and control of health services that ultimately will moderate cost increases and make medical costs more predictable to the government, the private sector, and the consumer (5). For example, during the 1950-1974 period, spending by federal, state, and local governments increased from $3 billion to $41 billion or from 26 percent to over 40 percent of total health expenditures, primarily due to the introduction of Medicare and Medicaid programs in the 1960's.

Only rough determinations can be made of the actual resource-use costs of radiological health services. The resources directly devoted to the prevention, diagnosis, treatment, rehabilitation, and research in specific health programs are represented by the financial outlays of public and private health insurance and other agencies, employers, and individuals and their families. For radiological health care delivery systems, these are sizeable costs and include both fixed and recurring expenditures for: (a) health services provided by radiologists and other physicians, hospitals, dentists, technologists, nurses, and other health personnel; (b) complementary commodities, such as x-ray film, radiopharmaceuticals, chemicals, and other medical supplies; (c) public and private health agency programs, mass x-ray screening and surveys (e.g., breast, for early diagnosis of cancer) for some disease programs or socio-economic groups; (d) a part of capital expenditures for construction of radiological equipment, and expensive recurrent maintenance, used in the provision of radiology health services and the production of complementary radiological health goods; (e) a part of costs of training radiological health services personnel; and (f) radiological research.

While some progress has been made in the development of cost estimates for the radiological health care expenditures which encompass most of these categories of outlays, estimates in current use fall far short of even a complete account of both public and private expenditures for hospital and radiological services. However, some economic information is available. During 1970, approximately 210 million medical and dental x-ray and radioisotope examinations were performed in the United States. If it is assumed that the average cost per examination to the medical consumer was $22, as for a chest x-ray examination, then the direct recurring expenditures for all chest x-ray examinations to the population would be in excess of $1.4 billion; and for all diagnostic radiological health services and supplies in that year the cost would be approximately $4.6 billion (Table VI.2). If, conservatively, it is further assumed that this represents two-thirds of the costs of all resource-use for radiological services, the remainder including the capital expenditures for construction, purchase, and maintenance of health plant and x-ray facilities used in the provision of radiological health services, and in the production of complementary health goods, then a conservative estimate of all direct costs or resource-use directly devoted to all radiological health care services and supplies approaches $7 billion. This represents a radiological health expenditure per person of approximately $35 or 7 percent of the per capita expenditure for all health services.

A brief tabulation of the distribution of diagnostic x-ray examinations only obtained from the USPHS 1970 X-Ray Exposure (XES) Study (3) and based on the average 1975 medical professional services fee schedule (Connecticut Medical Services (15) can provide a simplified accounting of the cost of the medical consumer. Based on some 140 million medical and 68 million dental x-ray examinations in the United States in 1970, the costs to the medical and

TABLE VI.2

Resource-Use Costs Model

Distribution and Dollar Costs of Medical and Dental X-Ray Examinations in the Year 1970

Body Area Type of Examination	Number[1] (million)	Cost[2] ($) per Examination
Chest (thorax)	65	22
Upper abdomen	15	22
Lower abdomen	17	39
Upper extremities	10	17
Lower extremities	12	22
Head, neck, and other	10	22
Gastrointestinal series	6.6	50
Barium enema	3.5	50
All other fluoroscopic examinations	2.5	40
Dental radiography	68	12

1/ (From XES, 1970 Survey) (3)
2/ (From CMS, 1975) (15)

dental consumer can be shown to approximate $4.5 billion (Table VI.2). Thus, the estimated resource-use costs to the health services consumer, assuming that the medical and dental x-ray costs determined represent approximately two-thirds of all direct resource-use costs for all radiological health services, would be therefore estimated to approximate $7 billion.

b. Resource-Loss Model

The loss of resources arising from sickness and injury may be considered in terms of human resources lost or impaired as a result of the deleterious effect on society's productivity caused by sickness (12,13). This may be justified in the sense that only limited resources are available and that without sickness and injury, health services would be unnecessary so that the available resources would be free for other productive uses in society. Part of the total economic cost of illness is the actual loss of economic (human) resources, notably human labor, available to a productive society. In order to quantitate the loss, one method would be to value the loss in dollars. For such valuation, it is necessary to estimate the productive output "foregone." In other words, if sickness and injury could be prevented, eliminated, or limited in time, it would be important to determine how much productive gain (benefits to society) those persons who are presently ill would have contributed to societal resources.

In general, the effects of sickness and injury on the amount of human labor available for productive purposes may be considered under three main categories (9,10,13): (1) debility, or the loss of productive capacity of individuals while at work; (2) disability, or the loss of working or otherwise productive time; and (3) death, or the actual loss of workers. Based on this definition, various stages in achieving a calculation of the estimated previous output lost may be considered. However, these stages assume that for any estimate of work-loss due to a disease or injury, if it were not for the disease, those sick persons in the productive age groups stricken by the disease would have otherwise been well and therefore employed and productive. Clearly, certain conceptual problems arise which make precise estimates of resource-loss difficult to compute. For example, the assumption that the resource-loss as a result of illness is productive human labor must make some provision for costs of certain societal activities which are necessary concomitants, such as unemployment and the impact or direct effect of unemployment on the incidence of disease and injury. Some provision must account for persons who are disabled or die prematurely who would otherwise be in good health. Further assumptions must also be made for the time scale (the loss in a given time period), the loss of working time of the individual in relation to the work-force participation (for any single period estimate, the resource-loss of the young who have not as yet entered into the productive work-force, and of the retired-aged, would be zero or possibly a negative value), loss of output due to debility, and so on.

For the purposes of the resource-loss model which follows, a one-year estimate may be chosen. It is conceptually a much simpler time scale, and it involves fewer assumptions. Within the framework of the model, certain provisions can be made for the loss of a productive work-life (i.e., total disability or death). However, no attempt is made for allowances which include future discounting, productivity increases, and consumption. In the model calculation of resource-loss estimates for chest x-ray examinations in diagnostic radiology, therefore, the loss in production may be viewed as a loss within a given time period; the one-year estimate for 1970 (for which the most recent data are available) is chosen. Provision for loss over a productive life of children who have not yet entered the work force is made, and it is assumed that all individuals who have entered the workforce have remained.

Certain costs and benefits in health are intangible circumstances which can be readily identified, but not easily quantified, e.g., the production or relief of pain, the development of anxiety or its amelioration, or the extent of physical or psychological discomfort. Such circumstances have a direct impact on the health and well-being of individuals, affecting debility or disability, and indirectly the capacity for a productive life. Other circumstances, such as the prevention of death or reduction in lives lost, can be readily quantified in an arithmetic sense, but cannot be valued with precision in a market sense. These intangible costs and benefits are, nevertheless, extremely important, and must be taken into account in any benefit-cost analysis model, since they are essential for decision-making processes in health care services systems. It is difficult to gain some idea of the importance of such intangibles, and in practice, attempts at assessment of their relative importance, however imprecise, are frequently made by perception techniques on grading questionnaires.

4. Reduction of Risk Model

A major criticism of the resource-loss benefit-cost model is that it implies that a person's health and, therefore, life can be valued by the productive capacity of the individual. The simplest application of the model is that of an increase in the risk of death. Similar application can be made in relation to increase in risk of injury as well as death. Thus, there are two basic objections to the resource-loss model: (1) it fails to take into account different levels of valuation of more productive members of society, and (2) it assumes that society values an individual only in terms of his economic contribution. The model does not take into account such intangible circumstances as pain, discomfort, anxiety, bereavement, and attempts to deter death.

Furthermore, society recognizes and invests heavily in the non-productive members of society, e.g., health and education for children, and health and well-being of elderly, retired persons. Thus, the non-productive persons in society could represent a substantial cost (or benefit) value to society to be added to the lost productivity factors, affecting the net contribution to society. The values determined by the resource-loss model should be modified to assess the net contribution to society, and such values must therefore be considered as the lower level that society would be prepared to place on an individual's life.

An approach to an assessment of how society might value non-economic losses (or gains) may be considered in terms of the risk, and its avoidance. In other words, an extension of the resource-loss model can be applied to reduced risk of death, and to reduced risk of injury and disease. The model is symmetrical; for example, an increase in number of diseases and deaths is a recognized by-product of growth of economic activity resulting from the increased use of ionizing radiations in medical practice. A reduction in the number of diseases and deaths can be a by-product of some growth of an economic activity such as in preventive medicine.

In benefit-cost analyses of health programs, the traditional approach has been that: (1) the major purpose of the program is to save lives and reduce illness; (2) death or illness avoided means that a loss of human production may be avoided; (3) the problems center on valuing the benefits per life saved or per illness avoided; (4) the economic value of a human life saved varies according to a variety of factors, including age, and can be determined with some precision; and (5) the non-economic value of a human life can be ascertained based on the costs society will spend to save a life. None of these factors, except possibly the last, takes into account the multiplicity of variables entering into the effects of disability, debility, and death, among the most important of which are the risks leading to illness and death. Rationality in decision-making assumes that it is possible to decide how much to spend to reduce various kinds of risk. Furthermore, since societies, both in their public and private capacity, do incur measureable costs to reduce recognizable risks, it has been demonstrated amply that their valuation of diminution in risk can be determined, and even quantitated from their behavior (16).

F. Application of Resource-Loss Benefits Model to Diagnostic Radiology

1. Concepts and Parameters

In terms of benefit and costs, three categories of x-ray examinations and radioisotope scanning procedures can be classified (17). In each of these, it is possible to identify particular benefits to be balanced against a cost or detriment, either economic or to health, or both.

The first category comprises the vast majority of x-ray and radioisotope examinations which are performed for the immediate medical needs of the patient who is ill. The traditional policy of American medicine is that of attempting to restrict this category of examinations to those which would control and confirm clinical diagnoses tentatively established by physical and other methods of clinical diagnosis, and would affect subsequent management of the patient. A benefit-cost analysis by the physician at the time is invariably impractical and would be unlikely to affect the decision to perform the necessary radiological examinations. Nevertheless, the extent, frequency, and degree of completeness of these examinations are subject to wide variation in different hospitals, health agencies, or private offices. It would appear that many of these procedures could possibly be carried out with much lower doses of radiation to the patient with little decrease in benefit.

The second category is the mass-screening or case-finding diagnostic x-ray examinations which expose large health populations. These x-ray surveys are designed as part of disease-control programs, e.g., mammography for breast cancer, to improve the health and well-being of the individual and of the community. Until recently, little effort was placed on assessment of cost-effectiveness and benefits to be derived, but authorities responsible for planning and measuring health resources are now beginning to submit such mass-screening programs to careful benefit-cost analysis. The benefits are those current costs of the disease which are averted by the program and such benefits are compared with the resource-costs of the program. A small group of screening x-ray examinations include those tests directed at "exclusion" of diagnoses rather than confirmation, usually on a selected basis in the course of management of symptom-free patients. In all, a relatively small proportion of all x-ray examination procedures may fall into the screening-survey category.

The third category includes a large group of specific x-ray examinations carried out for preventive medical and dental needs of persons who are otherwise in good health and for occupational, insurance, medical-legal, and psychological purposes. These should be evaluated to assess the particular benefits to be derived by the person actually exposed.

Table VI.1 lists some important statistics from the 1970 United States Public Health Service X-Ray Exposure Study (3) on which the following resource-loss benefits model estimates are based.

Diagnostic (investigative radiological health care services may be looked upon as part of the resource-use of health resources directly devoted to the prevention, diagnosis, treatment, and rehabilitation of diseased or injured persons who are temporarily or permanently lost from the total human labor force during that year. One component of the resource-use costs is the cost of off-setting disease and impairment which cause a loss of human labor and, therefore, of economic resources. Hence, these are resource-use costs to offset resource-losses, but on the assumption that an estimate of work-loss (which may be valued in dollars by health economists) as a measure of productivity loss due to illness may be determined by the productivity of the persons affected by the disease who would have otherwise been employed. The investigative x-ray or radioisotope examination may be considered an essential part of the health services system necessary to return these persons who are ill to full productivity in society. As such, the x-ray examination may be evaluated by its beneficial effect on the overall resource-loss costs, that is, the prevention of debility, disability or death, thereby being of benefit to the patient who is ill.

In this model, assumptions must be made on the value or benefit of a particular x-ray or radioisotope examination in each case, the efficiency of the procedure, the precision of the x-ray diagnosis, and its influence on the effectiveness of management of the patient affecting prognosis of that individual. Furthermore, it must be assumed that all these activities, however subjective and qualitative, can be quantified and that each is maximal in order to provide a rough estimate of benefit (i.e., resource-use costs less prevented resource-loss costs) which can be computed.

It must be recognized that these are assumptions derived at the present time solely from impressions of clinical radiological practice in medical care services in the United States. Such assumptions are subjective and speculative, since no quantitative data are available on which to base more firm figures. The following assumptions are made for purposes of the model only:

(a) It has been arbitrarily assumed that of all medical x-ray examinations performed in the year 1970, perhaps 85% did not help to prevent any resource-loss directly benefiting the patient exposed; that is, the x-ray examination, however essential and beneficial to the patient, prevented no debility or disability in the year of exposure, 1970. Included here would be the majority of examinations in the second and third categories outlined above.

(b) It has been arbitrarily assumed that approximately 8% of all medical x-ray examinations in 1970 prevented minimal debility or disability in the patient exposed in the year 1970. This would include primarily confirmatory diagnostic x-ray and radioisotope examinations for already clinically diagnosed disease established in first category or examinations (e.g., most chest x-rays, bone and joint x-ray examinations, sinus x-rays, etc., that is, those x-ray examinations already established in the diagnosis and management of chronic diseases such as chronic lung disease, arthritis, headaches,and sinusitis, etc.).

(c) It has been arbitrarily assumed that perhaps some 4% of all medical x-ray examinations prevented moderate debility and disability in the patient exposed in the year 1970. These examinations would include more specialized examinations usually performed in hospitals, e.g., gastrointestinal series for peptic ulcer, cholecystograms for gallbladder disease, excretory urograms for hypertension or renal disease, etc.

(d) It has been arbitrarily assumed that approximately 2% of all medical x-ray examinations prevented major debility or disability in the patient exposed in the year 1970. Such examinations would include the diagnosis and management of serious fractures of the skull, spine or hip, gastrointestinal studies for surgical emergencies, specialized vascular x-rays for peripheral vascular disease, etc.

(e) It has been arbitrarily assumed that approximately 1% of x-ray examinations prevented complete disability in the patient exposed in the year 1970. Here, such specialized x-ray examinations as cerebral angiography, coronary angiography, and other specialized neurovascular and cardiovascular x-ray procedures would be included. The x-ray examinations usually comprise a sequence of investigative procedures, frequently involved in the diagnosis and management of patients with diseases which represent the leading causes of death--diseases of the heart and blood vessels, cancer, cerebrovascular disease, and accidents. A special category in this group would be those x-ray examinations which resulted in the prevention of death in the year 1970, that is, prevention of the resource-loss over a productive work-life of the individual stricken by the disease.

A cost estimate of the value of each x-ray procedure may be considered in relation to the resource-loss as a result of sickness, that is, loss of human labor. Simplifying the valuation, there are basically two stages in calculating the estimated productive output foregone: 1) estimating the loss in productive work time, and 2) assigning a money value to the output that his lost work time represents (12). This is done to obtain an index which takes into account all aspects of disability prevention and includes lives saved (or deaths prevented). This index is a relative value; it may then be converted to a dollar value which represents the composite value of the loss of productive output attributable to debility, disability, or death. However, dollar valuation represents only one form of calculating a relative value; the values cited in the models are illustrative of the analytical process only and should not be taken as actual measures. The economic value may be used to represent a very rough estimate of the expected increase in productive output that would occur if the loss of resources due to sickness were diminished or ultimately eliminated.

In the simplified model, such conceptual problems as the impact of unemployment and full employment, multiple diseases in the same individual, time scales, loss of working time, work-force participation of the young and retired-aged, and loss of output due to debility, disability and death, present formidable problems beyond the scope of the present approach. However, the net output method of calculating the economic worth of a person's life, is one quantitative concept which may be used and which, inpart, takes many of the complex variables into account.

To derive the benefit of a particular class of x-ray examinations, the resource-use cost may be used to offset the resource-lost cost by assigning a relative value to the disability-prevention of the individual. A number of assumptions must be made. It has been arbitrarily assumed: 1) that the average per capita income of the working individual at the present time may be determined; e.g., it may be $50 per day for 200 working-days per year; 2) that a minimum disability represents a 10% loss of working-days per year; i.e., from 1 to 20 days, a mean of 10 days in this model, the productivity loss would average approximately $500 in one year; 3) that a moderate disability represents the loss from 10% to 20% of the working-days per year or from 21 to 40 work-days; in this model the productivity loss would average approximately $1,500 in one year; 4) that a major disability represents the loss from 20% to 40% of the working-days per year, or from 41 to 80 work-days, a mean of 60 work-days; in this model the productivity loss would average approximately $3,000 in one year; 5) that total disability represents the complete loss of all working days in one year; this may occur due to injury or sickness at any time during the year. This would be the loss from 40% to 100% or from 81 to 200 work-days; a mean of 140 days; in this model the productivity loss would average approximately $7,000 in one year; 6) that in this special situation of death of a productive individual, the entire future lifetime earnings of the individual is lost in that year; that is, a loss of approximately $300,000 in that year. However, since the loss can occur at any time during the productive life-span, then one-half, or approximately $150,000 of the life-time earnings may be considered as a resource-loss in that year. In this case, the prevented-loss of the entire future expected life-time earnings of the individual would result. It has been assumed that only a very small percentage of the total disability category comprises this special situation.

2. Valuation of Benefits from Diagnostic Radiology

Table VI.3 illustrates the application of the model to determine an estimated valuation of the resource-loss prevented (extent of disability days prevented) by diagnostic chest x-ray examinations in the year 1970 based on the "resource-loss benefits model." The stream of medical benefits in the determination of a benefit-cost ratio, fitted to the present trends and not discounted for the future, can be estimated. Conversion to dollar value results in total benefits of $14.6 billion. The dollar cost (from Table VI.2) of the chest x-rays are estimated at $1.43 billion. It is noteworthy that in 1971 approximately 5.1 disability work-days were lost per employed person per year (77.4 million persons employed) (20).

A complete summary of the total dollar value benefits from diagnostic radiology derived in 1970 in the United States by the entire population based on a "resource-loss benefits model" would require a much more complete knowledge of the patterns of medical x-ray examinations than is available at the present time. Very rough assumptions can be made on the percentage distribution of the disability-prevention values for the various categories of medical x-rays, and these concepts may not apply at all in estimating benefits from dental x-ray examinations or diagnostic nuclear medicine procedures. Furthermore, dollar valuation represents only one form of calculating a relative value; the values cited here are illustrative of the analytical process only and should not be taken as actual measures. The dollar value of $14.6 billion for benefits derived from chest x-ray examinations may be considered as a conservative estimate, since the model is based primarily on only one premise, vis., the improvement of health through prevention of disease and effective diagnosis and treatment of illness contributes to the efficiency of the population's productive capabilities. The model takes into account the effect of the resource-losses of those persons who have not as yet entered the work force (e.g., children under age 18), non-employed, but productive persons in society (e.g., housewives), and those who have left the productive population (e.g., the elderly-retired), through the mechanism of resource-transfer benefits. The model does not take into account costs which would otherwise have been transferred from the well to the sick. The model also attempts to quantify effects of debility and disability due to illness on productivity of the individual.

TABLE VI.3
RESOURCE-LOSS BENEFITS MODEL

Estimated Work-Loss Prevented (Dollar Value-Benefits) from Diagnostic Chest X-Ray Examinations (*)

Extent of Disability Prevention (Work-days-Saved)	Days	Mean	Definition[1] (%)	Distribution[2] (%)	Number of Examinations (Millions)[3]	Dollar Benefit Factor/Exam [4]	Benefit[5] (10^9 dollars)
None		0	0	85	55.3	0	0
Minimal	(1-20)	10	10	8	5.2	500	2.6
Moderate	(21-40)	30	20	4	2.6	1,500	3.9
Major	(41-80)	60	40	2	1.3	3,000	3.9
Total	(81-200)	140	100	1	.6	7,000	4.2
				100%	65.0		$ 14.6 billion

1. Percentage disability-prevention

2. Percentage distribution of diagnostic chest x-ray examinations

3. Frequency of x-ray examination in millions (3)

4. Benefit factor per x-ray examination in dollars (work-value-day ($50) x mean number of days)

5. Work-loss prevented resulting in productive work-days in dollar value (frequency x benefit factor)

(*) Dollar valuation represents only one form of calculating a relative value, the values cited here are illustrative of the analytical process only and should not be taken as actual measures.

G. Application of Resource-Loss Costs Model to Potential Radiation Induced Somatic Disease from Diagnostic Radiology

1. Conceptual Problems

Conceptual problems arise in the development of a "resource-loss costs model" since in its simplest form it represents and assumes that the primary effect of sickness and death is on human labor available for productive purposes (12). The model assumes that persons who die from or are disabled by the disease would otherwise be in good health, that indirect costs of the disease cannot be readily summated, and that a time scale can be applied over a productive work life. Nevertheless, the concepts of loss of working time and indirect economic costs caused by disease and illness in populations have been examined (11) and are accepted in welfare economics. Certain objections arise on ethical grounds, understandably, such as the conversion of human lives to money terms, the difficulties in assessing human suffering, and the tendency to regard the savings of children's lives and those of other non-productive members of society as costs rather than gains. However, the economic costs of a disease or a death represents only one model for the evaluation of a health program and its efficacy; other models are equally valid for development of cost estimates of disease and death.

A "resource-loss costs model" for diagnostic radiological exposure could be developed in terms of estimates of somatic risks and potential genetic risks (1). Knowledge of the distribution of diagnostic x-ray and radioisotope examinations, the size of the populations examined, and the dose to the individual and to the population exposed is necessary (3). The somatic risks of special concern are cancer-induction, the increased radiosensitivity of the embryo and fetus (effects of antenatal radiography), and the consequences of possible mutation-induction in germinal cells resulting in genetic handicaps among the descendants of irradiated populations. Based on the premise that the resource lost as a result of radiation-induced illness and death is human labor, the model would assess the value of the loss by estimating the "output foregone" resulting from death, disability, or debility. The value of the productivity loss may then be estimated by 1) determining the loss of productive work-time, and 2) assigning a money value to the productive output that this lost work-time represents (12).

Table VI.4 contains estimates of the distribution of the numbers of diagnostic x-ray examinations of various body regions, numbers of persons, and radiation doses that are required for application in the model for estimation of risks and, therefore, costs. The estimate of dollar value costs for the potential deleterious effects (radiation cancer) of diagnostic chest x-ray examinations is based on the data in Table VI.4; dollar valuation represents only one form of calculating a relative value; the values cited here are illustrative of the analytical process only and should not be taken as actual measures.

The data in Table VI.4 may be used to estimate the total dollar value costs expected to result from radiation-induced cancers in adults derived in 1970 in the United States by exposure of the population in that year to

TABLE VI.4

Estimated Distribution of Diagnostic X-ray Examinations, Persons and Radiation Doses, --- United States, 1970 (A,D)

Body Area	Number X-ray Examinations (Millions)	Percentage Distribution[B]	Estimated Persons (Millions)[C]	Dose/Exam[D] (mrads)	Tissues at Greatest Risk
Thorax	65	51	39		thyroid, bronchus and lung
Chest, R[E]	49	38	29	40	bone marrow, breast, bone
Chest, PFG[E]	10	8	6	100	
Thorax	6	5	4	40	
Abdomen	32	25	19	100	stomach & colon, bone marrow, bone, uterus and ovary
Extremities	22	17	13	5	bone marrow, bone
Head, Neck, Other	10	7	5	50	thyroid, bone marrow, bone
TOTAL Medical	129	100	77		
TOTAL Dental	68	100	59	50	thyroid, bone marrow, bone

A. USPHS,XES Survey, 1970 (3)
B. Estimated from (3)
C. Estimate based only on examination distribution and rate
D. ICRP No. 16, 1970 (21)
E. R, Radiographic; PFG, Photofluorographic

diagnostic x-rays. The economic costs are based on the "resource-loss model" by converting the loss of life due to radiation neoplasia into loss of productive capacities of the affected population. The total economic value represents an estimate which does not include morbidity from causes other than radiation-induced cancer, or the costs of diagnosis and treatment of these individuals as patients. These latter costs would necessarily be included in the resource-use costs.

The somatic effects to be considered in the application of a resource-loss costs model include neoplasia in adults, effects on growth and development (developmental abnormalities and spontaneous abortions) and childhood neoplasia (1).

The large number and the diversity of body tissues exposed to x-rays during the various diagnostic examinations and wide variations in doses administered and in tissue sensitivity, preclude any precise assessment of the incidence of induction of neoplasia by radiation (2,21). However, from the evidence available, it appears that the low level radiation doses from medical and dental x-ray exposure during diagnostic procedures could be important in regard to cancer induction (1). It would appear that among the most important of these is the somatic dose to the bone marrow, the thyroid, the bronchus and lung, the stomach, the osseous tissues, and the breast (Table VI.4). The chest (thorax) x-ray examination encompasses all of these tissues, and this may be used in an illustrative example of the application of the resource-costs loss model; the following example demonstrates the method for calculation of estimates of dollar value-costs for potential somatic effects (radiation-induced neoplasia) of diagnostic chest x-ray examinations.

2. Valuation of Costs from Diagnostic Radiology

In 1970, the USPHS XES Survey (3), 65 million chest (thorax) x-ray examinations were carried out (Table VI.4). Of these, 49 million were radiographic examinations, 10 million were photofluorographic (PFG) and 6 million were other studies of the chest and thorax. The chest x-ray examination rate for children was less than for adults; 10 percent of the chest x-rays (or approximately 5 million examinations) were children under age 15, and the examination rate was 10 per 100 children. The estimated mean exposure per film for radiographic chest examinations was 27 mR (3). Assuming 2 film exposures per examination in half of these patients, and one film in the remaining investigative x-ray studies, then the average radiation dose to the tissues of the chest, including the thyroid, the bronchus and lung, the active bone marrow, the breast, and bone from adult radiographic examinations was about 40 mrads per examination (21), and thus, an additional 1 million person-rads to the exposed population. The total somatic tissue radiation dose to the exposed adult population due to the chest x-rays in 1970 therefore, would be approximately 3.2 million person-rads. This does not take into account the increased dose from photofluorographic examinations of the chest; however, the use of PFG chest examinations has been discontinued by the United States Public

Health Service and other health agencies through action by the Food and Drug Administration under authority of the Radiation Control for Health and Safety Act (P.L. 90-602) (22,23).

On the assumption of linearity of the dose-effect relationship (1,26), a conservative estimate of the excess cancer risk due to radiation exposure of these tissues would be one excess cancer case arising in 1 million exposed persons per year per rad. The radiation cancer risk due to chest radiological examinations in adults would be 3.2 excess cancers of the bone marrow, thyroid, bronchus and lungs, breast and osseous tissues of adults. If it is assumed that all children's chest x-rays delivered only half the dose, but that this is offset by the increased radiosensitivity of juvenile tissues, then an additional 0.2 million person-rads could result in 0.2 excess cancers in each of these tissues. The breast may be some 3 times more radiosensitive to cancer induction than the other tissues (1,2); the excess breast cancers expected, therefore, would be 4.8 excess cases. The thyroid in children may be about 3 times more radiosensitive than the adult thyroid tissue for radiation cancer induction (1); for thyroid cancers, therefore, approximately 3.9 excess cancers would be expected to occur in the entire population exposed to chest x-ray examinations. If it is further assumed that all radiation-induced cancers, including thyroid cancers, lead to death, then there would be, in each year following exposure, approximately 3.2 excess deaths due to leukemia induced in the bone marrow, 3.2 excess deaths from cancer of the bronchus and lung, 3.2 excess deaths from bone cancer, 4.8 excess deaths from breast cancer, and 4.1 excess deaths from thyroid cancer. The total would be 18.5 excess cancer deaths in the population exposed in the year 1970. Over a 10-year period, there would be 32 leukemia deaths; over a 25-year period there would be an additional 383 deaths, or a total of 408 cancer deaths. In the year 1970, this could therefore represent the loss of the life-time productive earnings of the adult individuals and children who do not enter the work-force, and thus potential economic productivity loss (work-loss) equal to (32 x $150,000) + (365 x $150,000) + (18 x $300,000) = approximately $64 million.

Valuation of costs of potential somatic effects of antenatal radiology can be used to estimate the dollar value costs derived in the United States in 1970 resulting from such x-ray exposure. Information is required on obstetrical and pelvimetric x-ray examinations, their distribution, the fetal doses, and the birth rate. The fetal and neonatal developmental abnormalities and loss (spontaneous abortions), and childhood neoplasia, are special categories arising from the radiosensitivity of the embryo and fetus exposed in utero. The dollar value-costs of the work-loss estimated by the "resource-loss costs model" must take account of the fact that the fetuses or children who die or are seriously disabled never enter the work-force, and the potential entire lifetime earnings of each of these individuals is lost.

The total dollar value-costs to society resulting from potential radiation-induced somatic disease arising from diagnostic medical radiation exposure to the United States population in the year 1970 can be estimated by means of the "resource-loss costs model." In the model illustrated, no attempt has been made to determine the extent of unspecified somatic disease and ill-health as a result of impaired physical and mental well-being. This might be mainfested in a decrease in the individual's work productivity, or possibly an increase in disability days, but such changes are too complex to be assessed in this model with any precision. For this reason, the total costs may be considered as a conservative estimate. The degree of improved well-being and health (which can decrease the extent of disability and increase the individual's work productivity) arising from the benefits of diagnostic radiological procedures may be considered as symmetrical with the losses (i.e., ill-health); the present model precludes determination of precise figures. The total economic value estimated in the application of the model largely represents the productive work-loss from the human labor force which can contribute to the gross productivity of society. The medical care costs must be discounted in the future, but would appear in the resource-use costs model estimates at a future date.

H. Application of Resource-Loss Costs Model to Potential Radiation-Induced Genetic Disease

The application of the resource-loss costs model to potential radiation-induced genetic disease and hereditary effects requires a great deal more information on the genetic risks from radiation that is presently available. The NAS-BEIR Report (1) presented a rough benefit-cost analysis of radiation exposure by measuring the future economic costs of potential genetic casualties. The approach used concepts of the resource-loss costs model to determine the genetic damage to be expected after one generation from one man-rem, and then equated this value to dollar costs of United States health services in 1970. This monetary value ranged from $12 to $120 per man-rem. A number of assumptions were implied and no attempt was made to analyze the numerous and complex variables involved in any comprehensive resource-loss costs model.

Based on the NAS-BEIR Report (1), the main classes of genetic disease and hereditary effects to be expected from radiation exposure include autosomal dominant traits, chromosomal and X-linked recessive diseases, congenital anomalies, recognized abortions, and a large, non-specific category of unspecified genetic illness. The autosomal dominant traits represent a broad spectrum of diseases in the fetus, neonatal infant, and growing adult. The model would require precise information on the expression of these diseases in the population, their incidences of morbidity and mortality, and age distribution; the birth and fertility rates of the exposed population; a knowledge of the doubling dose (or similar parameter) of radiation for mutational effects in man; a frequency distribution of diagnostic x-ray examinations affecting the gonadal dose, and hence the genetically significant dose, in both women and men; and an estimate of the loss to potential economic productivity (and direct costs of ill-health) in society of the individuals in future generations affected by the genetic disease, with appropriate future discounting.

Similar parameters would be required for recessive genetic traits, for congenital anomalies (e.g., those due to unbalanced chromosomal rearrangements and aneuploidy, and due to X-chromosome-linked recessive traits), for all other recognized abortions, and for a large and poorly understood class of genetic damage of unrecognized abortions that results in failure of the egg to implant or results in post-implantation death. This latter group of spontaneous abortions is too early to be detected, and occurs unrecognized within the first month of pregnancy. The contribution of radiation dose from diagnostic x-ray exposure to an increased incidence in this group cannot be ascertained. In such an analysis, this loss may possibly be considered as a future resource-loss and since the numbers of individuals affected may be extremely large, but the circumstances are natural consequences occurring in reproductive biology, this situation has not been considered to have an appreciable effect on human well-being.

Non-specific ill-health due to unspecified genetically determined disease, possibly resulting in diminished or poor physical and mental health is extremely difficult to assess (1). The 1972 NAS-BEIR Report (1) included an attempt to measure the economic cost of radiation resulting in unspecified genetic illness, and estimated a dollar cost of 1 rad. The contribution of the the total cost of all unspecified genetic illness could then be estimated from this figure, and the dollar cost would be distributed over many generations into the future (1), taking into account discounting into the future.

I. Summary of Economic Benefit-Cost Analysis of Diagnostic Radiology

Any examination of benefit-cost analysis of medical radiation would require a thorough understanding of all the categories of benefits and costs necessary to achieve a calculation to measure the effectiveness of diagnostic radiological investigative and therapeutic procedures in modern health care services in the United States. One very rough approach taken in the present analysis has been to develop medels based on resource-use costs, resource-loss costs, and resource-loss benefits. In the illustrative examples, the years 1970 and 1974 were chosen, since the data are available to permit a rough assessment of resource-use and resource-loss factors. However, certain of the calculations necessary must extend into the future and, therefore, must consider the effect of future discounting. The approach assumes that society invests in man, that there is an economic value of human life relative to the attainment of a state of optimal health, that economic costs of disease, injury, and death are measurable, and that the indirect basic economic costs of depressed health may be equated, in large part, to time lost from the full desired capacity or quality of life. The development of benefit-cost analysis of the economic impact of illness and death, and their prevention, are based on the assumption that each person has an economic value to society, and that if the individual becomes ill or dies before fulfilling his life expectancy there is a measurable economic loss generated because of the obviation of potential productivity.

Multiple models can be used to arrive at crude dollar-value costs and value-benefits, and these take into account either direct costs of services or indirect costs affecting health. From calculations of time lost from work force participation, estimates of the dollar value of lost economic productivity can be developed. Nevertheless, it is recognized that while dollar valuation may appear inescapable, economic terms remain marketplace terms. Therefore, they are inadequate to describe the true worth of a human life or the social value of the individual person. However, they do provide avenues to quantitate, in part, the socioeconomic impact of ill-health and death due to disease and injury. For decision-makers who are responsible for planning health activities, economic valuation, however crude, may assist in: 1) defining the important problems, 2) determining their magnitude, 3) describing tangible benefits and costs of problem solution, 4) determining program priorities, and 5) selecting program alternatives.

J. Application of Reduction of Risk Model

1. Mass X-ray Screening in Diagnostic Radiology

This model assumes that the reduction of the incidence of disease, suffering, and death is an activity to be regarded as a collective societal good. As an example, a societal or government scheme of early diagnosis of debilitating or morbid disease affecting a large population can be considered to save a certain number of lives annually. An advantage of the "reduction of risk" model is that it gives decision-makers the opportunity to assess the economic and social costs of a health service in terms of alternatives.

The use of mass screening programs in diagnostic radiology lends itself to this model. Two important illustrations may be considered from the second category group of diagnostic x-ray examination, vis., mass x-ray screening of the breast (mammography) for breast cancer, and mass x-ray screening of the chest for pulmonary tuberculosis and cancer of the lung.

For mass x-ray screening programs to be valuable and feasible, they should meet most of the following criteria: they should be safe, relatively inexpensive, simple to carry out, convenient for both the screened population and the personnel, reliable and sensitive, specific for the disease, and provide a good yield of curable cases. For pulmonary tuberculosis, mass chest x-ray screening fit many of these criteria when the yield of positive cases was high, and especially when effective chemotherapy was introduced and provided a method for treating the diseases successfully. Recent studies have demonstrated that current x-ray screening for lung cancer in older persons could possibly fulfill a number of these criteria, except that the yield of curable cases is extremely low (28). On the other hand, restricting x-ray screening to certain high-risk groups may not necessarily improve the yield of curable cases of neoplasia in some populations (e.g., lung cancer in heavy cigarette smokers, especially those with a chronic cough (29)), but may be of value in certain high-risk populations (e.g., the high incidence of breast cancer in American women (30)).

a. Mass X-Ray Screening of the Breast (Mammography)

Breast cancer is the leading cause of death from neoplastic disease among women in the United States; it occurs in some 6 percent of all women during their lifetime. Approximately half of these women die within 15-20 years after the initial diagnosis, a third of the deaths in that population result from breast cancer. Furthermore, during the period 1935-1963, the age adjusted mortality for American women over 25 years of age fell from 15.2 deaths per 1,000 population to 9.3 per 1,000, a decrease of almost 40 percent, whereas deaths from breast cancer in the same age group remained much the same at 40 cancer deaths per 100,000 population (30).

Cancer detection programs have emphasized the importance of early diagnosis in breast cancer. The introduction of mammography for early diagnosis of the disease provides certain benefits, but whether mass x-ray screening surveys for breast cancer in women are worthwhile depends in large measure on the prevention or delay of deaths and on its acceptability and cost to the general population. The Health Insurance Plan of New York (H.I.P.) Study of Shapiro and his colleagues (30) suggests that mammographic screening (combined with clinical palpation) in a carefully controlled population of women 40 to 65 years of age detects cancer at an earlier stage, and that earlier diagnosis and treatment results in improved survival, at least in the short term of the first 6 years thus far studied. However, since in this study breast cancer was detected on average only 20 months earlier, frequent re-examination would be essential, and even with annual x-ray re-examination, almost a third as many breast cancers were detected solely by the women themselves.

Irwig (31) has suggested that the detection of breast cancer by combined palpation and mammography is costly, both economically as well as to the general well-being of the patient. At present-day resource-use direct costs, a mammogram (unilateral or bilateral) costs approximately \$33 (15). Assuming decreased direct costs on the basis of mass screening, and adding costs of combined clinical palpation and mammography, an estimate of a minimum of \$30 per examination would be conservative. At the expected cancer detection rate of 1-2 cases per 1,000 women examined, the cost may be estimated to be about \$20,000 per breast cancer detected. If the H.I.P. Study (30) result of an approximately 44 percent decrease in deaths at 6 years is assumed, the cost of each additional case surviving up to 6 years would be \$45,000. Thus, in the 31,000 women aged 40-65 years examined, improved survival over the 6-year period thus far studied occurred in 36 cases, at a cost of \$1.6 million. It follows that, if the mass mammographic screening program were extended to include most women in the United States aged 40-65 years, perhaps 31 million women, then the cost of all cases surviving up to 6 years would be approximately 1,000 times, or \$1.6 billion. The productivity resource-loss prevented as a result of the cancer deaths prevented on the other hand would be approximately (\$50 x 200 work-days x 6) = \$60,000 per life saved, or ($36 \times 10^3 \times \$60,000$) = approximately \$2.2 billion. From the dollar valuation point of view, the benefit-cost ratio would only be about 1.4 after 6 years. The data demonstrate a differential in deaths between study and control groups and it appears that more than 36,000 deaths may ultimately be avoided.

The problem is compounded by the fact that the breast is a relatively radiosensitive tissue to the induction of cancer, and that mammography is a relatively high-dose x-ray examination. The radiologic techniques for mammography vary; average radiation doses in controlled programs range from 1-5 rads for the skin and underlying tissues of the breast. The risks of induced neoplasms as a result of irradiation of the bone marrow and the body as a whole are acceptably small.

A rough estimate of the radiation hazards from all malignancies associated with the mammographic examinations in the Health Insurance Plan Study (30) has been determined based on the following assumptions: 1) 20,000 women examined with an average of 3.2 x-ray studies per woman; 2) the breast tissue dose was 2 rads, the lung dose 0.2 rads, the bone marrow dose 0.04 rads, and other tissue dose 0.02 rads; 3) the carcinogenic risk is linear, the women were exposed at exact age 55, the mid-point of the plateau period was 14.5 years with respect to leukemia, and 30 years with respect to all other organs, and years of life expectancy are not taken into account. The number of expected deaths from cancer, therefore, was breast, 3.5; lung, 0.2; leukemia, 0.05; and other, 0.01; the total is approximately 4 cancer deaths at all sites due to radiation exposure. The data suggest that the cancer deaths appear to be equivalent to approximately one-tenth of the breast cancer deaths avoided in the first 6 years, suggesting benefit/cost ratio of a factor of 10. However, mammographic procedures may employ radiation doses much greater than in the controlled Hospital Insurance Plan Study, and the benefit would be correspondingly reduced. Furthermore, mammography studies indicate that the procedure for women under age 50 does not result in a decrease in breast cancer deaths and the risk of radiation-induced cancer is greater, so that mass mammographic x-ray screening of younger age-group women would appear to involve a net hazard.

If the assumptions based upon the H.I.P. Study were to be extended to the entire population at risk, then it would be estimated that a minimum of 6,000 radiation-induced cancer deaths over a lifetime would result in the female population in the United States. This would occur since all women would be x-rayed annually until death, increasing the radiation dose, and hence the radiation cancer risk in women who would not have developed the disease spontaneously. However, something less than 10 times that number of breast cancer deaths would be avoided. While this appears to be an acceptable benefit-cost ratio, there are effective ways of improving the safety margin, mainly by decreasing the radiation dose to as low as practicable and by selecting for examination the female population which would appear to greatest risk of breast cancer. The use of clinical palpation alone would have some reduction in death rate. Furthermore, the H.I.P. Study indicated that a biopsy procedure was required in some 5-10 cases per 1,000 women screened on mammography. Some 80 percent of the women biopsied were found to have benign disease of the breast. This is costly, not only from the point of view of a surgical procedure, but probably to a much greater degree in terms of personal and family anxiety and well-being.

When all factors are considered, the present x-ray screening methods for breast cancer are time-consuming and costly; to be effective, they require frequent x-ray re-examination and the false-positive rate is high. The low incidence and detection rate of breast cancer in women under age

40 does not justify mass x-ray screening in this population. Economically, the net benefit-cost ratio is less than 1.0, and thus better and cheaper screening methods are required. At the present time, it would appear that selected mammography should be restricted only to "high-risk" groups in early detection screening programs (e.g., women with strong family predisposition to breast cancer, patients with clinical signs and symptoms, patients with previous breast cancer).

b. Mass X-Ray Screening of the Chest

The experience in the United States has demonstrated that the case-finding capability of mass screening photofluorographic (PFG) chest x-ray examinations for pulmonary tuberculosis control and early detection of cancer of the lung no longer is of value. The costs and risks are too high for the benefits derived, the incidence of pulmonary tuberculosis has decreased and case-finding techniques using immunological tests are cheaper and more readily available, and "early" diagnosis of cancer of the bronchus by PFG x-ray screening techniques have not influenced the survival or quality of life of those patients treated for the neoplastic disease.

In the instance of mass x-ray screening of the chest for lung cancer, dollar resources of the community could hardly be sufficient to afford the expense incurred in the small yield of cured cases of lung cancer based on the premise of early detection through semiannual PFG chest screening. Furthermore, the biological nature of the disease, in respect to detection and diagnosis, precludes the effective use of PFG screening for lung cancer; economic resources might be better spent on prevention and on examining the relationship of the human behavior of smoking to chronic lung disease (29).

2. Chest Radiography

X-ray examinations of the chest comprise 40% to 50% of the diagnostic radiological studies performed in the United States; in 1970, over 65 million chest x-rays were carried out on 129 million persons (3). In large part, the chest x-ray examination is now considered as an extension of the clinical history and physical examination in medical practice, and no longer a specialized investigatory examination. As a result, the radiation dose to the population is high; more than 50% of the population bone marrow dose is due to chest x-rays (32,33). If it is assumed that the average cost to the medical consumer is over $20 per examination, then almost $1.5 billion is spent annually in the United States for this examination alone.

Sagel et al. (34) analyzed 10,000 chest examinations in a large university hospital and, based on the incidence of positive findings and the low yield of positive results, demonstrated that: 1) routine screening chest radiographs, obtained because of hospital admission or elective surgery, are not warranted in patients under 20 years of age; 2) the lateral x-ray projection should be eliminated from routine screening chest examinations in patients 20-39 years of age; 3) the lateral x-ray projection should be part of the examination whenever chest disease is suspected. Thus, while occasionally a treatable condition may be discovered on routine (but clinically unnecessary) chest radiography in an otherwise healthy child or young adult to the age of 20 years, it would appear prudent to eliminate routine chest radiography as a standing medical order in this age group.

Approximately one-third or 21 million of the chest x-ray examinations of the population are of persons under age 29. In 1970, 47 percent of the thoracic examinations were performed with 2 or more x-ray films compared with 31 percent in 1964; the increase was largely due to the use of lateral views for routine chest examinations (3). Thus, if it is assumed that two-thirds of the examinations in the under-29 year group were in the "routine" category, then 14 million examinations did not require lateral x-ray projections at all. If, by eliminating lateral projections, the cost of these examinations were decreased to half, then approximately $11 x 14 million or $150 million would be saved annually, or about 10 percent of the total dollar cost. A commensurate decrease in bone marrow dose would be expected, as well, particularly in patients under age of 20 years. In these circumstances, where screening for tuberculosis is the major concern, routine tuberculin skin testing is a much more practical method, as well as being medically, biologically, and economically sound, particularly in comparison with chest radiography.

It would appear, therefore, that the value of the "routine" chest x-ray examination in patients without specific clinical indications should be examined carefully, particularly in regard to diagnostic yield, likelihood of diagnostic accuracy, and cost-effectiveness as regards increased time, costs and exposure. A logical extension of this would be the use of the chest x-ray examination of the child and young adult, and the use of screening programs, as alternative techniques, such as tuberculin skin testing, which would appear more effective in large populations without evidence of clinical chest disease.

3. Special High-Dose Diagnostic Procedures

The five leading causes of death in 1974 in the United States account for over 75 percent of the total number of deaths (35). The death rate for diseases of the heart, the leading cause of death, was 353.1 per 100,000 population. The estimated death rate for malignant neoplasms, including neoplasms of lymphatic or hematopoietic tissues, was 169.5 per 100,000 population; for cerebrovascular disease, 97.2 per 100,000 population; for accidents, 48.9 per 100,000 population; and for influenza and pneumonia, 25.7 per 100,000. Except for malignant neoplasms, in which the death rate increased by 1 percent from 1973, all other rates of the leading causes of death were reduced from the previous year.

In the diagnosis and management of these diseases, medical radiation plays a substantial role. The decrease in mortality rates is in part due to increased efficiency in the use of medical diagnostic x-rays and radioisotopes, and in the curative (and palliative) treatment of neoplastic diseases with therapeutic radiation. Whereas heart and circulatory diseases, cerebrovascular diseases, and neoplastic diseases result in substantial costs to society in terms of disability and productivity loss, the investigatory procedures in medical practice to diagnose, assess, and manage these diseases also represents a high cost both in risk and economic costs (36).

It would be worthwhile, therefore, to apply the reduction of risk and costs models to high-use examinations in x-ray services for high-morbidity (and thus, high disability) and high-mortality diseases and high-dose situations. Three areas about which useful information is available are:
1) cardiovascular disease, and particularly ischemic heart disease,
2) cerebrovascular and neurological disease, and 3) x-ray examinations in pregnancy.

a. Cardiovascular Disease

The influence of advances in diagnostic radiology on the medical practice of cardiology and the management of cardiac disease is well documented (37). In the management of patients with ischemic heart disease, i.e., coronary artery disease, the leading cause of coronary thrombosis, radiological techniques have now become routine methods of investigation.

It is estimated that more than 100,000 coronary angiographic x-ray examinations are currently carried out each year in the United States. Assuming a dose of 20 rads per examination, approximately 2 million person-rads result, with perhaps an expected 2 excess cancers of the bronchus and 2 excess cancers of the mediastinal tissues (e.g., lymphoma) occurring after 15-25 years. However, such excess cancer cases will only arise in patients who survive ischemic heart disease in their advanced year. This excess is placed in perspective when it is recognized that the death rate of diseases of the heart in 1970 was 3,620 per million population and in 1974 it fell to 3,530 per million population. Thus, the excess risk of dying from heart disease would still remain approximately 1,000 times greater than from radiation cancer. Furthermore, even if these advanced radiological techniques are effective in reducing mortality by only 1 percent, and perhaps as much as 3 percent, then the relative benefits derived from lives saved would be 10-30 times the costs possibly resulting from radiation injury.

However, the economic costs of cardiac catheterization and angiocardiography are not small. An analysis for the costs of cardiac catheterization procedure for 1973 carried out in a large university hospital (38) indicated that approximately 720 cardiac catheterization procedures were performed at a total cost of nearly $300,000. The cost for actual utilization, therefore, was approximately $482 per procedure. These costs are primarily fixed, that is, resource-use costs (e.g., equipment, space, personnel). If each procedure required 4 days of hospitalization for admission, investigatory testing and evaluation, then an additional $600 must be added for hospital fee costs, and perhaps $100 for tests. Loss of productive work time may be estimated at $200. The total economic costs, therefore, would be approximately $1,400 per patient, or $1.4 billion each year.

b. Cerebrovascular and Neurological Disease

Cerebrovascular and neurological diseases represent the third highest cause of mortality in the United States; in 1974, the estimated death rate for cerebrovascular disease was 97.2 per 100,000 population, a decrease of 5 percent from the rate of 102.1 for 1973, and the lowest level since before 1969 (35). In large measure, the development of new techniques in neuroradiology have made possible the early diagnosis of curable disease; however, in the proliferation of complex invasive techniques, the costs of radiological health care in neurology have escalated.

In the United States in 1970, there were 4.2 million skull x-ray examinations (3); 17 million x-ray films were exposed at an average dose of 330 mrads per film (3,21). The total somatic dose to the active bone marrow and the eye would be ($4.2 \times 10^6 \times 4.1 \times 330 \times 10^{-3}$ rads) = approximately 5.7 million person-rads, and the excess neoplastic diseases to be expected would be approximately 6 leukemias and 6 bone cancers. The productivity loss from 12 cancer deaths would be $1.8 million. It would be substantially less if perhaps half the number of x-ray films were used per patient examination for a normal skull x-ray.

A recent cost-effectiveness study on cranial computerized axial tomography (39) demonstrated a potential savings of $2.2 million per diagnostic facility based on 2,500 examinations per year, savings of inpatient and outpatient health services, and the decrease in the number of invasive neuroradiological investigatory studies performed and the number of beds occupied (number of admissions and duration of hospital stay) by neurological patients. Whereas it is too early to attempt to evaluate the diagnostic and therapeutic benefit and the elimination of hazard for patients in economic terms, nevertheless, the immediate benefits of this new non-invasive technique for studying the brain appear impressive.

K. X-Ray Examination of Pregnant Women

ICRP No. 9 (40) included a recommendation that, when medically appropriate, x-ray examinations of the female abdomen and pelvis should be limited when pregnancy is probable and to delay these examinations to a time when an embryo or fetus cannot be exposed to radiation. The most common radiographic procedures resulting in significant exposure of the fetus *in utero* are x-ray pelvimetry and the obstetrical abdomen. However, the efficacy of these examinations on improvement of delivery and decrease in fetal mortality and morbidity has not been established. The need for screening pregnant patients for cephalopelvic disproportion or fetal postmaturity can be carried out with diagnostic ultrasound, which thus far appears relatively harmless. In the future, x-ray pelvimetry and the obstetrical abdomen may become unnecessary, and possibly abandoned to be replaced entirely by safe and reliable techniques of antenatal ultrasonography.

L. Consideration of Reduction of Risk in Radiotherapy

1. Malignant Disease

Radiation therapy is being used more frequently, alone and in conjunction with surgery or chemotherapy, for the cure or palliation of malignant disease in the individual. The radiation doses are high, are confined, and are tissue-limiting, and the cancer age group is relatively advanced. Thus, the radiation exposure contributes little to the genetic dose affecting future populations. Furthermore, whereas there may be a savings of large numbers of individual lives, or prolongation of individual lives in comfort and dignity, the net effect is at most a marginal impact on total life expectancy in the society.

In 1974, in the United States the estimated death rate due to malignant neoplasms, including lymphatic and hematopoietic tissues, was 169.5 per 100,000 population, an increase of less than 1 percent from the rate of 167.3 for 1973. This represents 18.5 percent of the total deaths in that year, and was the second leading cause of death in the United States. The yearly incidence of malignant disease is about 3,000 new cases per million population, or some 600,000 new cases occur annually. Most patients are treated with surgery and radiotherapy; about half of all cancer patients receive radiotherapy in the course of their disease. Cancers of the lung, colon-rectum, breast, uterus, prostate, and kidney-bladder, which represent about half of all cancers, are the major causes of death due to neoplasia.

If the survival rate is approximately 130 cases per 100,000 population, then the deaths avoided each year due to all treatment is approximately 260,000 in the entire population. The death rate rises substantially over the age of 55 years. If it is assumed further that the survival after 5 years following treatment is below 50% for major cancers, and that 50% of all cancer patients receive radiotherapy, then some estimate of productivity loss can be determined. Assuming a mean age of 55 years at the time of treatment and 600,000 new cancer patients each year, then 300,000 cancer patients are treated with radiation, half for cure and half for palliation of their disease. Only half (or 150,000) of these patients survive to the age of 60 years, many of whom may be considered cured of their disease, when life expectancy rates at age 60 years are taken into account. Thus, if it is assumed that without radiation treatment the treated patients would have died within 5 years, then radiotherapy given in the year 1974 saved the lives of $(300{,}000) - (169.5/10^5 \times 2\text{x}10^8/2)$ = approximately 130,000 patients in that year, but only about 65,000 will survive after 5 years. If the average remaining lifetime of the cured patients at age 55 can be determined, then the maximum survival resulting from radiation therapy could be estimated.

The resource-use cost model may be used in the evaluation of delivery of radiation therapy services. Bloom et al. (41) studied 16 hospitals in New England and determined the cost of facilities, equipment and personnel, and demonstrated that the cost of providing radiation therapy for cancer invariably exceeded the income derived, and many of the direct costs per treated patient ranged from about $150-$600, and this cost was greatest in the high patient-load teaching hospitals and cancer centers due to the larger and more costly equipment and personnel. However, if 300,000 patients per year receive radiation therapy for malignant disease, and if it is assumed that half of these patients are treated for palliation (lower cost) and the remaining patients receive a curative regime (higher cost), then the average costs to the consumer may be very roughly estimated at (150,000 x $150) + (150,000 x $600) = approximately $112.5 million. If a most conservative estimate is used, since the direct (and indirect costs) of providing radiation therapy services invariably far exceeds the income derived, and the total of all radiation costs per treated patient was at the maximum value ($600), and there are comparable amounts for all other hospital services and for hospitalization, then the average cost per patient would be $1,800, and the total cost of all health services for providing radiation therapy would be (300,000 x $1,800) or approximately $540 million. The benefit-cost ratio based on economic terms could then be determined. This model does not include intangible factors such as comfort, relief of pain, and other non-quantifiable circumstances surrounding the treatment of cancer patients.

In this context, however, it must be emphasized that such an analysis should be considered in terms of the total oncological services to society; it should have little relevance to the individual patient under treatment for neoplastic disease. For many reasons, and especially for ethical and moral reasons, society has chosen to spend heavily out of the limited resources available for health care of the individual. This invariably precludes the need for impractical economic benefit-cost analysis of direct diagnostic or therapeutic radiological health care in the individualized situation for a given patient (see page 177).

2. Non-neoplastic Disease

At the present time, no precise estimate of the number of patients treated with radiation for non-neoplastic diseases is available in the United States. The practice of radiation treatment for diseases other than cancer has diminished in recent years, particularly as alternative methods of treatment in clinical pharmacology have become available and equally effective. Included here, for example, are treatment for bursitis, tinea infections, certain viral warts, peptic ulcer, and arthritis. In the treatment of non-neoplastic disease, the radiation doses are less than in the treatment of cancer. It would appear prudent to reduce or eliminate this practice wherever possible, and to employ alternative methods of treatment, thereby avoiding unnecessary radiation exposure, and lessening any possible contribution to the gonadal and somatic doses, and consequent effects. The problem is being studied by the National Academy of Sciences.

M. Reduction of Dose from Medical Radiation Usage

Steps necessary to decrease population exposure from medical radiation, particularly the avoidance of unproductive radiation exposure, may be considered in three main areas: 1) radiological equipment and installations; 2) radiological techniques; and 3) clinical and other professional judgment. Recent progress in these areas includes the following:

1. Radiological Equipment and Installations

Improved standards of diagnostic x-ray equipment efficiency and x-ray beam collimation and alignment have resulted in significant reduction of the dose to the patient from scattered radiation, or from the direct beam, and in the improvement in the quality of the x-ray image. Appropriate filtration of the x-ray beam has helped in obtaining maximum information from many types of radiological examinations.

In diagnostic nuclear medicine, reductions in dose have been achieved by imaging devices and cameras, the use of short-lived isotopes, and by the application of computer technology.

In therapeutic radiology reductions of dose to nontarget tissues have been achieved by the introduction of linear accelerators, precision of dosimetry obtained with the application of computer techniques, and the use of new interstitial sources.

2. Radiological Techniques

Appropriate positioning devices for patients and improved techniques for the visualization of internal organs (e.g., contrast media, tomography, computerized axial tomography) have helped reduce the number of unnecessary repeat diagnostic x-ray examinations resulting primarily from unsatisfactory radiographic technique or inaccurate clinical interpretation. Shielding devices (such as gonadal shields now readily available) and beam collimation have been developed which eliminate a large fraction of unnecessary x-ray exposure of radiosensitive organs, such as the testis, ovary, bone marrow, and thyroid. Improved diagnostic x-ray receptors (screens and films) associated with correct radiation exposure, grids, film processing, and film viewing have been developed. The restriction of the use of photofluorography (mass radiography), has led to the elimination of unnecessary exposured at relatively high levels of dose to large populations.

3. Clinical and Other Professional Judgment

Assessment of the clinical value of certain high-dose procedures of fluoroscopy (e.g., pediatric chest fluoroscopes for cardiac disease) and cinefluorography (e.g., avoiding cystourethrography in children) has resulted in a decrease and possible elimination of many examinations. The training of radiological personnel for improved knowledge, skill and operations to meet the continuously increasing demand for clinical radiological services has led to the development of uniformly high standards and quality of health care.

4. Radiation Protection

A principal objective of radiation protection in medicine is to use the radiological procedure most likely to produce the desired result with a dose as low as practicable and acceptable to the patient and to the staff. This implies that some radiation risk always exists, and if this is the case some benefit-cost balance must be attempted. The patient himself benefits directly from the examination performed as part of his treatment. Such considerations are more difficult for other medical sources of population exposure, where the individual irradiated may be asymptomatic and therefore not a patient and therefore may not necessarily be one of those for whom benefit is claimed. From the point of view of radiation protection, therefore, the problems involve the balance between the value of dollar expenditure necessary to reduce the already small exposure risks, and of similar financial expenditure on other societal problems. Based on scientific evidence, a continued effort must be pursued to maintain radiation exposure in medicine to the minimum possible.

The greatest benefit to the patient and to the population with the least possible radiation exposure involves a continued examination of the radiological health care delivery system, and includes a decision-making process for the selection of patients to be examined, the training and education of personnel and the methodology of carrying out the radiation procedures, the evaluation of the total radiological facilities provided, the efficiency of diagnostic accuracy affecting treatment, and the cost-effectiveness of the system.

APPENDIX TO CHAPTER VI

FEDERAL AND STATE REGULATIONS

1. The Radiation Control for Health and Safety Act

The Radiation Control for Health and Safety Act of 1968, Public Law 90-602, 42 U.S.C. 263b et seq. (22) is a government regulation enacted by Congress to provide for the protection of the public from unnecessary radiation from electronic products. The Act recognized that because dangers may exist from ionizing and non-ionizing radiation, there is a need to establish control programs. These include the development and administration of performance standards for control of radiation from electronic products and research into the effects and control of radiation. Radiation covered in the Act includes any ionizing electromagnetic or particulate radiation emitted from an electronic product as the result of the operation of an electronic circuit, and thus includes all medical and dental x-ray machines in diagnostic radiology, and high energy x-ray machines used in radiation therapy.

The Act assigns to the Bureau of Radiological Health of the Department of Health, Education, and Welfare (Food and Drug Administration, United States Public Health Service) the responsibility to define, set, interpret, carry out and enforce the standards and regulations for an electronic products radiation control program. The regulations for the administration and enforcement of the Act of 1968 (48) are compiled and revised periodically, and publication of all regulations as amendments or deletions to the Act are issuances of the Federal Register and the Code of Federal Regulations, Title 21 (21 CFR Subchapter J). The two important sections of the Act include: 1) the radiation safety performance standard for diagnostic x-ray systems and their major components (43); and 2) regulations imposing necessary responsibilities on manufacturers, assemblers, distributors, and dealers of such equipment (44).

a. The Diagnostic X-Ray Equipment Standard

The Federal Performance Standard for diagnostic x-ray systems 1) determines performance standards for components of diagnostic x-ray systems, and 2) requires that they be certified by the manufacturer as being in compliance with the standard (43). The final standard for diagnostic x-ray systems Code of Federal Regulations, Title 21, Sections 1020.30 - 1020.32, was issued in the Federal Register on August 15, 1972, and applies to specified components manufactured after August 1, 1974, including x-ray tube housing assemblies, x-ray controls, x-ray high-voltage generators, fluoroscopic image assemblies, x-ray tables and cradles, x-ray film changers and cassette holders, and beam-limiting devices. The standard is an equipment performance standard and does not specify equipment design features, thereby permitting manufacturers to determine how to achieve levels of equipment performance in compliance with the standard. Furthermore, the standard does not regulate diagnostic x-ray equipment users, i.e., it does not regulate the practice of medical or dental radiological health nor does it control the use of x-ray equipment for a specific purpose.

Whereas the important provisions of the standard are aimed at equipment component design and hence performance, provision is made for x-ray exposure and beam quality, and for fluoroscopic exposure limits. The standard requires that x-ray systems provide improved exposure reproducibility and linearity of the x-ray output, and prescribes certain acceptable levels of x-ray beam quality which may be achieved through appropriate filtration. Further, the standard establishes maximum exposure rates for fluoroscopic equipment; patient-entrance exposure is limited to 10 R per minute for fluoroscopic equipment with automatic exposure or brightness control, and an exposure limit of 5 R per minute for equipment with high-level control operated in normal position and unlimited in the high-level position.

b. Regulations for Assembly and Reassembly of Diagnostic X-Ray Systems

Section 21 CFR 1000.16 provides for control and improvement of assembly and reassembly of the components of diagnostic x-ray systems (44), and at present, extends into the period after August 1, 1979. In this regard, the standard designates the role and responsibilities of the x-ray equipment manufacturer and assembler, including installation requirements and appropriate record keeping.

2. State Radiation Regulatory Control

The Radiation Operations Staff of the Food and Drug Administration's Executive Director of Regional Operations assists and advises the Bureau of Radiological Health on regional and state radiological health activities in regard to the reduction of unnecessary human exposure to man-made radiation. The Radiation Operations Staff also coordinates all radiological health activities at the Federal-State level. In the past 25 years, 47 states and Puerto Rico have enacted specific laws for the regulation of ionizing radiations, whereas the remaining 3 states and the District of Columbia assume radiation protection standards under general public health laws. In 1974, state and local agencies spent more than $10 million for radiation control activities. Only a small part of these funds and the manpower are directed toward compliance programs of medical x-ray activities in each State. Most frequently, statutes designate the State health department as the agency responsible for radiation protection with the authority to adopt regulations (45).

In 1974, there were 138,491 medical x-ray machines reported in the United States; 86% were registered, and of these 79% had been inspected at least once in the past. Of the 27,000 machines inspected in 1974, more than 27 percent were found to be in noncompliance to State regulations or recommendations (6). There were 142,875 dental x-ray machines reported in the United States; 85.5 percent of these have been registered. Some 75 percent of all machines have been inspected at least once (25,000 in 1974), and some 80 percent of those inspected were in compliance with State regulations or recommendations (6).

CHAPTER VI

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GLOSSARY

GLOSSARY

ABCC: Atomic Bomb Casualty Commission

Absolute Risk: Product of assumed relative risk times the total population at risk. The number of cases that will result from exposure of a given population.

Absorption Coefficient: Fractional decrease in the intensity of a beam of X or gamma radiation per unit thickness (linear absorption coefficient) per unit mass (mass absorption coefficient), or per atom (atomic absorption coefficient) of absorber, due to deposition of energy in the absorber. The total absorption coefficient is the sum of individual energy absorption processes (Compton effect, photoelectric effect, and pair production).

Accelerator (Particle): A device for imparting large kinetic energy to electrically charged particles such as electrons, protons, deuterons and helium ions. Common types of particle accelerators are direct voltage accelerators, cyclotrons, betatrons, and linear accelerators.

Alpha Particle: A charged particle emitted from the nucleus of an atom having a mass and charge equal in magnitude to a helium nucleus: i.e., two protons and two neutrons.

ALAP: As Low as Practicable

ALARA: As Low as Reasonably Achievable

ANL: Argonne National Laboratory

Atomic Mass: The mass of a neutral atom of a nuclide, usually expressed in terms of "atomic mass units." The "atomic mass unit" is one-twelfth the mass of one neutral atom of carbon-12; equivalent to 1.6604×10^{-24} gm. (Symbol: u).

Attenuation: The process by which a beam of radiation is reduced in intensity when passing through some material. It is the combination of absorption and scattering processes and leads to a decrease in flux density of the beam when projected through matter.

Average Life (Mean Life): The average of the individual lives of all the atoms of a particular radioactive substance. It is 1.443 times the radioactive half-life.

BEAR Committee: Advisory Committee on the Biological Effects of Atomic Radiation (Precursor of the BEIR Committee).

BEIR Committee: Advisory Committee on the Biological Effects of Ionizing Radiations.

Benefit-Cost: A systematic process of comparative evaluation of all significant benefits and costs of an activity and alternative courses, including as major components the benefits, risks and costs related to health, life span and quality of life.

Benefit-Cost (applied to Medical Radiation): A quantitative evaluation of the health risks and economic costs to society resulting from medical radiation exposure in relation to the benefits to the health and well-being of society and its members derived from the application of ionizing radiations in medicine.

Beta Particle: Charged particle emitted from the nucleus of an atom, with a mass and charge equal in magnitude to that of the electron.

BLIP: Base-Line-In-Plant

Bone Seeker: Any compound or ion which migrates in the body preferentially into bone.

CAA: Clean Air Act

Carrier: A quantity of non-radioactive or non-labeled material of the same chemical composition as its corresponding radioactive or labeled counterpart. When mixed with the corresponding radioactive labeled material, so as to form a chemically inseparable mixture, the carrier permits chemical (and some physical) manipulation of the mixture with less label or radioactivity loss than would be true for the undiluted label or radioactivity.

Cation: Positively charged ion

CEQ: Council for Environmental Quality

Chamber, Ionization: An instrument designed to measure a quantity of ionizing radiation in terms of the charge of electricity associated with ions produced within a defined volume.

COPEP: Committee on Public Engineering Policy

Cost-effectiveness: The economy with which a given task, program or policy is carried out.

Curie: The special unit of activity. One curie equals 3.700 x 10^{10} nuclear transformations per second. (Abbr. Ci.) Common fractions are:

Megocurie: One million curies (Abbr. MCi)
Microcurie: One millionth of a curie (3.7 x 10^4 disintegrations per second. Abbr. µCi.)
Millicurie: One-thousandth of a curie (3.7 x 10^7 disintegrations per second. Abbr. mCi.)
Nanocurie: One-billionth of a curie (Abbr. nCi)
Picocurie: One-millionth of a microcurie (3.7 x 10^{-2} disintegrations per second. Abbr. pCi)

Daughter: Synonym for decay product.

Decay Product: A nuclide resulting from the radioactive disintegration of a radionuclide, formed either directly or as the result of successive transformations in a radioactive series. A decay product may be either radioactive or stable.

Decay, radioactive: Disintegration of the nucleus of an unstable nuclide by spontaneous emission of charged particles and/or photons.

DHEW: Department of Health, Education and Welfare

Discounting Procedures: The method of calculating the present value of a future sum to be symmetrical with the compound rate of increase.

Dominence: A case where as between two alternatives one produced both a greater quantity of the desired result and at less cost than the other with which it is compared.

Dose: A general form denoting the quantity of radiation or energy absorbed. For special purposes it must be appropriately qualified. If unqualified, it refers to absorbed dose.

Absorbed Dose: The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest. The unit of absorbed dose is the rad. One rad = 100 ergs per gram.

Cumulative Dose: Total dose resulting from repeated exposure to radiation.

Dose Equivalent (DE): Quantity that expresses all radiations on a common scale for calculating the effective absorbed dose. It is defined as the product of the absorbed dose in rads and certain modifying factors. The unit of DE is the rem.

Genetically significant dose (GSD): The gonad dose from medical exposure which, if received by every member of the population, would be expected to produce the same total genetic effect on the population as the sum of the individual doses actually received. The GSD can be expressed algebraically as:

$$GSD = \frac{\Sigma D_i N_i P_i}{\Sigma N_i P_i}$$

D_i = Average gonad dose to persons age i who receive x-ray examinations

N_i = Number of persons in population of age i who receive x-ray examinations

Pi = Expected future number of children for person of age i

Ni = Number of persons in population of age i.

Maximum Permissible Dose Equivalent (MPD): The greatest dose equivalent that a person or specified part thereof shall be allowed to receive in a given period of time.

Median Lethal Dose (MLD): Dose of radiation required to kill, within a specified period, 50% of the individuals in a large group of animals or organisms. Also called LD_{50}.

Permissible Dose: The dose of radiation which may be received by an individual within a specified period with expectation of no significantly harmful result.

Threshold Dose: The minimum absorbed dose that will produce a detectable degree of any given effect.

Doubling Dose: The amount of radiation needed to double the natural incidence of a genetic or somatic anomoly.

Dose, Fractionation: A method of administering radiation, in which relatively small doses are given daily or at longer intervals.

Dose, Protraction: A method of administering radiation by delivering it continuously over a relatively long period at a low dose rate.

Dose rate: Absorbed dose delivered per unit time.

Electron Volt: A unit of energy equivalent to the energy gained by an electron in passing through a potential difference of one volt. Larger multiple units of the electron volt are frequently used: KeV for thousand or kilo electron volts; MeV for million or mega electron volts. (Abbr. eV, 1 eV = 1.6×10^{-12} erg.)

EPA: Environmental Protection Agency

ERDA: Energy Research and Development Administration

Exposure: A measure of the ionization produced in air by X or gamma radiation. It is the sum of the electrical charges on all ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in air, divided by the mass of the air in the volume element. The special unit of exposure is the roentgen.

Acute exposure: Radiation exposure of short duration
Chronic exposure: Radiation exposure of long duration by fractionation or protraction.

External Costs: Costs falling on third parties not party to a market transaction, thus representing social costs not registered in market price or costs.

Fission, Nuclear: A nuclear transformation characterized by the splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy.

Fission Products: Elements or compounds resulting from fission.

Fission Yield: The percentage of fissions leading to a particular nuclide

FDA: Food and Drug Administration

FRC: Federal Radiation Council

Nuclear Fuel Cycle: The sequence of steps, such as utilization, reprocessing, and refabrication, through which nuclear fuel passes.

Fusion, Nuclear: Act of coalescing two or more atomic nuclei

FWPCA: Federal Water Pollution Control Act

Gamma Ray: Short wavelength electromagnetic radiation of nuclear origin (range of energy from 10KeV to 9MeV) emitted from the nucleus.

Gram Atomic Weight: A mass in grams numerically equal to the atomic weight of an element.

Gram Molecular Weight (Gram-Mole): Mass in grams numerically equal to the molecular weight of a substance.

Gram-Rad: Unit of integral dose equal to 100 ergs.

Half-Life, Biological: The time required for the body to eliminate one-half of an administered dosage of any substance by regular processes of elimination. Approximately the same for both stable and radioactive isotopes of a particular element.

Half-Life, Effective: Time required for a radioactive element in an animal body to be diminished 50% as a result of the combined action of radioactive decay and biological elimination.

$$\text{Effective half-life} = \frac{\text{Biological half-life X radioactive 1/2-life}}{\text{Biological half-life + Radioactive 1/2-life}}$$

Half-Life, Radioactive: Time required for a radioactive substance to lose 50% of its activity by decay. Each radionuclide has a unique half-life.

ICRP: International Commission on Radiological Protection

ICRU: International Commission on Radiation Units and Measurements.

Incidence: The rate of occurrence of a disease within a specified period of time; usually expressed in number of cases per million (10^6) per year.

Ion: Atomic particle, atom, or chemical radical bearing an electrical charge, either negative or positive.

Ion exchange: A chemical process involving reversible interchange of ions between a solution and a particular solid material such as an ion exchange resin consisting of a matrix of insoluble material interspersed with fixed ions of opposite charge.

Ionization: The process by which a neutral atom or molecule acquires a positive or negative charge.

Primary ionization: In collision theory; the ionization produced by the primary particles as contrasted to the "total ionization" which includes the "secondary ionization" produced by delta rays.

Secondary ionization: Ionization produced by delta rays.

Ionization density: Number of ion pairs per unit volume.

Ionization path (track): The trail of ion pairs produced by an ionizing radiation in its passage through matter.

Isotopes: Nuclides having the same number of protons in their nuclei, and hence the same atomic number, but differing in the number of neutrons, and therefore in the mass number. Almost identical chemical properties exist between isotopes of a particular element. The term should not be used as a synonym for nuclide.

Labeled Compound: A compound consisting, in part, of labeled molecules. By observations of radioactivity or isotopic composition, this compound or its fragments may be followed through physical, chemical, or biological processes.

Latent Period: The period or state of seeming inactivity between the time of exposure of tissue to an injurious agent and response.

LD_{50} (Radiation Dose) See: Dose, Median Lethal.

Linear Energy Transfer (LET): The average amount of energy lost per unit of particle spur-track length.

Low-LET: Radiation characteristic of Electrons, x-rays, and Gamma Rays.
High-LET: Radiation characteristic of protons or fast neutrons

Average LET is specified to even out the effect of a particle that is slowing down near the end of its path and to allow for the fact that secondary particles from photon or fast-neutron beams are not all of the same energy.

Linear Hypothesis: The assumption that a dose-effect curve derived from data in the high dose and high dose-rate ranges may be extrapolated through the low dose and low dose range in zero, implying that, theoretically, any amount of radiation will cause some damage.

LWR: Light Water Reactor

Man-Rems: See Person-Rems

Marginal (incremental) benefits or costs: The amount by which total costs (benefits) are increased due to a change of one unit on the output of the process in question. Mathematically, it represents the first derivative of the total cost (benefit) function.

Market-incured Costs: Costs arising out of the need to pay factor services (final consumption services) their market rates of hire (price).

Maximum Credible Accident: The worst accident in a reactor or nuclear energy installation that, by agreement, need be taken into account in deriving protective measures.

Medical Exposure: Exposure to ionizing radiation in the course of diagnostic or therapeutic procedures. As used in this report, the term includes:

1. Diagnostic radiology (e.g., x-rays)
2. Exposure to radioisotopes in nuclear medicine (e.g., Iodine-131 in thyroid treatment)
3. Therapeutic radiation (e.g., cobalt treatment for cancer)
4. Dental exposure

Micron: Unit of length equal to 10^{-6} meters. (symbol μ)

Morbidity: 1. The condition of being diseased.
2. The ratio of sick to all persons in a community

NAS-NRC: The National Academy of Sciences - National Research Council

NHTSA: National Highway Traffic Safety Administration

NCRP: National Council on Radiation Protection and Measurements

Neoplasm: Any new and abnormal growth, such as a tumor. The term "neoplastic disease" refers to any disease which forms tumors, malignant or benign.

NRC: Nuclear Regulatory Commission

Nuclide: A species of atom characterized by the constitution of its nucleus. The nuclear constitution is specified by the number of protons (Z), number of neutrons (N), and energy content; or, alternatively, by the atomic number (Z), mass number A=(N+Z), and atomic mass. To be regarded as a distinct nuclide, the atom must be capable of existing for a measurable time. Thus, nuclear isomers are separate nuclides, whereas promptly decaying excited nuclear states and unstable intermediates in nuclear reactions are not so considered.

Person-Rems: The product of the average individual dose in a population times the number of individuals in the population. Syn: man-rems.

Plateau: A period of above-normal, relatively uniform, incidence of morbidity or mortality in response to a given biological insult.

PWR: Pressurized Light Water Reactor

Prevalence: The number of cases of disease in existence at a certain time in a designated area.

Quality Factor (QF): The linear-energy-transfer-dependent factor by which absorbed doses are multiplied to obtain (for radiation protection purposes) a quantity that expresses -- on a common scale for all ionizing radiations -- the effectiveness of the absorbed dose.

Rad.: The unit of absorbed dose equal to 0.01 j/kg in any medium.

Radiation:

1. The emission and propagation of energy through space or through a material medium in the form of waves; e.g., the emission and propagation of electromagnetic waves, or of sound and elastic waves.

2. The energy propagated through space or through a material medium as waves. The term radiation or radiant energy, when unqualified, usually refers to electromagnetic radiation. Such radiation is commonly classified by frequency: Hertzian, infrared, visible, ultra-violet, x-ray, and gamma ray.

3. Corpuscular emissions, such as alpha and beta radiation, or rays or mixed or unknown type, as cosmic radiation.

Background radiation: Radiation arising from radioactive material other than the one directly under consideration. Background radiation due to cosmic rays and natural radioactivity is always present. There may also be background radiation due to the presence of radioactive substances in other parts of the building, in the building material itself, etc.

External radiation: Radiation from a source outside the body.

Internal radiation: Radiation from a source within the body (as a result of deposition of radionuclides in body tissue).

Ionizing radiation: Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, in its passage through matter.

Secondary radiation: Radiation resulting from absorption or other radiation in matter. It may be either electromagnetic or particulate.

Radioactivity: The property of certain nuclides of spontaneously emitting particles or gamma radiation or of emitting particles or gamma radiation or of emitting x-radiation following orbital electron capture or of undergoing spontaneous fission.

Artificial radioactivity: Manmade radioactivity produced by particle bombardment or electromagnetic irradiation.

Natural radioactivity: The property of radioactivity exhibited by more than fifty naturally occurring radionuclides.

Radioisotope: A radioactive atomic species of an element with which it shares almost identical chemical properties.

Radionuclide: A radioactive species of an atom characterized by the constitution of its nucleus. In nuclear medicine, an atomic species emitting ionizing radiations and capable of existing for a measurable time so that it may be used to image organs and tissues of the body.

Radiosensitivity: Relative susceptibility of cells, tissues, organs, organisms, of any living substance to the injurious action of radiation. Radiosensitivity and its antonym radioresistance, are currently used in a comparative sense, rather than in an absolute one.

Rate, Recovery: The rate at which recovery takes place after radiation injury. It may proceed at different rates for different tissues. "Differential recovery rate": Among tissues recovering at different rates, those having slower rates will ultimately suffer greater damage from a series of successive irradiations. This differential effect is considered in fractionated radiation therapy if the neoplastic tissues have a slower recovery rate than surrounding normal structures.

Rays: Alpha: Beams of helium nuclei (2 protons and 2 neutrons)
Beta: Beams of electrons or positrons
Gamma: Beams of high-energy photons from radioactively decaying elements
X: Beams of mixed lower energy photons
Neutron: Beams of neutrons
Proton: Beams of protons

Reactor Breeder: A reactor which produces more fissle material than it consumes; i.e., has a conversion ratio greater than unity.

Reactor Converter: A reactor which produces fissile atoms from fertile atoms, but has a conversion ratio less than one.

Reactor, Nuclear: An apparatus in which nuclear fission may be sustained in a self-supporting chain reaction.

Relative Biological Effectiveness (RBE): The RBE is a factor used to compare the biological effectiveness of absorbed radiation doses (i.e., rads) due to different types of ionizing radiation; more specifically, it is the experimentally determined ratio of an absorbed dose of a radiation in question to the absorbed dose of a reference radiation required to produce an identical biological effect in a particular experimental organism or tissues. The RBE is the ratio of rem to rad. (If 1 rad of fast neutrons equalled in lethality 3.2 rads of KVP x-rays, the RBE of the fast neutrons would be 3.2).

Relative Risk: The ratio of the risk in those exposed to the risk to those not exposed (incidence in exposed population to incidence in control population).

Rem: A special unit of dose equivalent. The dose equivalent in rems is numerically equal to the absorbed dose in rads multiplied by the quality factor, the distribution factor, and any other necessary modifying factors. The rem represents that quantity of radiation that is equivalent -- in biological damage of a specified sort -- to 1 rad of 250 KVP x-rays.

Roentgen (R): The special unit of exposure. One roentgen equals 2.58×10^{-4} coulomb per kilogram of air.

SDWA: Safe Drinking Water Act

Sigmoid Curve: S-shaped curve, often characteristic of a dose-effect curve in radiobiological studies.

Softness: A relative specification of the quality or penetrating power of x-rays. In general, the longer the wave length the softer the radiation.

Specific Activity: Total activity of a given nuclide per gram of a compound, element, or radioactive nuclide.

SSRCR: Suggested State Regulation for Control of Radiation

Thermography: A non-invasive diagnostic radiological imaging technique which uses infra-red radiation to display the temperature distribution emitted by the surface which characterizes the temperature distribution of the various underlying organs and tissues of the body.

Threshold Hypotheses: The assumption that no radiation injury occurs below a specified dose level.

Ultrasonography: A non-invasive diagnostic radiological imaging technique which uses acoustic radiation and the acoustic properties of biological structure to display the structure and function of various organs and tissues of the body.

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation.

Weighting Factor: The fractional weight by which a future sum is multiplied to obtain any intermediate year's time equivalent value, in turn derived from the compound interest formula.

X-rays: Penetrating electromagnetic radiations whose wave lengths are shorter than those of visible light. They are usually produced by bombarding a metallic target with fast electrons in a high vacuum. In nuclear reactions, it is customary to refer to photons originating in the nucleus as gamma rays, and those originating in the extranuclear part of the atom as x-rays. These rays are sometimes called roentgen rays, after their discoverer, W.C. Roentgen.

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